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Biology and Medicine

MEDICAL GAMMA-RAY SPECTROMETRY

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BASIC PRINCIPLES OF SCINTILLATION COUNTING FOR MEDICAL INVESTIGATORS

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MEDICAL GAMMA-RAY SPECTROMETRY

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INTRODUCTION: MEASURING RADIATION FROM A PATIENT

Since radioisotopes can be administered harmlessly to patients if the dose is kept small, they are coming into use more and more widely in medical research and diagnosis. It often becomes important to find out how much of an administered isotope has been collected in a given organ – for example, iodine-131 in the thyroid gland – and one way to determine this is to count the gamma rays coming from that organ[1]. Underlying this kind of measurement, however, is the assumption that the gamma-ray count is proportional to the amount of radioactive material present, and we must recognize that this will be true only if certain conditions are fulfilled. For example, if we double the radioiodine content of a patient's thyroid gland, without changing the gland's dimensions or position, we will double the gamma count detectable externally. Here the rule of proportionality holds. But if we should set up a small test tube of radioiodine, out in the laboratory air, and find that it counts twice as much as a patient's neck, we might be very wrong to conclude that there is twice as much iodine in the test tube. Here the rule of proportionality breaks down because the two counting situations are not similar. For reasons that will become apparent in a moment, the number of gamma rays reaching a detector depends not only on the source but on *what surrounds the source*, and in the foregoing comparison the surrounding material is air in one case and the neck tissues in the other. One might guess that the neck tissues absorb some of the radiation, thus causing an error, but more is involved in this problem than simple absorption, for sometimes the neck count may actually be too high rather than too low, depending on the type of detector used for the measurement. Thus the process of measuring radioisotopes buried inside a patient can be a tricky business.

The fundamental trouble is that gamma rays, or gamma photons[2], are apt to interact with matter as they pass through it. They collide with the atoms and knock some of the orbital electrons loose – hence the term "ionizing radiation". The denser the material, the more interactions there will be; thus there are many in lead, fewer in a patient's tissues, very few in air, and none in a vacuum.

In an interaction of this sort the photon delivers some or all of its energy to the electron, and the latter comes flying out of its atom with a velocity that depends on the amount of energy it has acquired. If the photon's energy is not very high, the electron often receives all of it, in which case we call the process a *photoelectric interaction*. Here the photon vanishes and a high-speed *photoelectron* emerges. More energetic photons are likely to transfer only part of their energy, in which case there will be two products of the interaction: a high-speed electron and a secondary photon carrying less energy than its parent primary. This process is called a *Compton interaction*, after the physicist who first investigated it; the electron is referred to as a *Compton electron* and the secondary photon is a *scattered* or *degraded* gamma ray (Fig. 1). The high-speed electrons produced in both types of interaction collide repeatedly with other atoms and produce ionizations of their own, thus dissipating their kinetic energy. Similarly, the scattered gamma rays may undergo further interaction and produce more ions. If the absorbing material is thick enough, it will absorb substantially all of the liberated electrons and scattered gamma rays, in

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[1] Alpha and beta particles are of little use to us here, for nearly all of them are stopped by the patient's tissues before they can get out.

[2] By way of review, we may recall that X rays and gamma rays belong to the same family as the familiar rays of visible light. Since the physicists have not yet decided whether this kind of radiation consists of waves ("rays") or particles ("photons"), we are free to take our choice, and here it is easier for us to think of them as particles – electrically neutral, submicroscopic bullets shot out of the radioactive atoms. These photons all travel with the speed of light (1000 feet per microsecond in a vacuum), and, just as a bullet packs a wallop, each photon carries a certain amount of energy with it. The amounts of energy are so tiny, however, that we need special units in which to talk about them. The usual unit of energy in the centimeter-gram-second system is the dyne-centimeter or erg; the gamma-ray unit of energy is the electran-volt ("ev"), which is 1.6 million-millionths of an erg. In harmony with other metric units, one *thousand* electron-volts is a "*kilo*-electron-volt" (kev), and one *million* of them is a "*mega*-electron-volt" (Mev). One Mev is therefore 1.6 millionths of an erg – a pretty small amount of energy, but nevertheless "supervoltage" by X-ray standards.

Visible light – say orange-colored light with a wavelength of 600 millimicrons – has an energy of about 2 electron-volts, or 2 ev; ordinary X rays have energies in the range of perhaps 1 to 300 kev; cobalt-60 gives off two highly penetrating gamma rays with energies up around 1250 kev, or 1¼ Mev.

which cases all the energy brought in by the primary photon is expended in producing ions in the absorber. The greater the energy of the incoming ray, the more atoms will be ionized.

While we are talking about Compton scattering, we should note that it sometimes makes gamma rays appear to go around corners: a source can affect a detector even if it is out of sight – for example, behind a block of lead. This happens only if a scattering medium is located within the field of vision of the detector, for unless a gamma ray interacts it continues onward in a straight path. When it scatters, however, the direction of the scattered ray is rarely the same as that of the parent primary, and therefore if you make no distinction between the two, "a" gamma ray can start out in one direction and end up going in another. Some instruments are designed to tell us *where* a buried radioisotope is, and they are likely to make mistakes unless they can distinguish between primary and scattered rays. A distinction is possible because the energy is always lowered in the scattering process, and accordingly if the instrument is appropriately energy-sensitive it can keep out of trouble.

There is a third way in which a gamma ray can interact with an absorbing body, and this is by the process of *pair production*. It never occurs unless the energy of the incoming photon exceeds 1,020 kev (= 1.02 Mev), and its contribution becomes significant only if the radiation energies get up above the 2-Mev level, which is unusual in medical work. When pair production occurs, the entering gamma ray expends its energy in "creating" a positron[3] and an electron out of nothing; this requires 1.02 Mev, and if there is any energy left over, the positron and the electron carry it away in the form of energy of motion. The electron goes on its way producing ionizations in the usual manner. The positron, however, is short-lived; it very quickly combines with an unattached electron in the neighborhood and the phenomenon of *annihilation* occurs. The positron and electron neutralize each other and vanish, and in their place there appear two new gamma rays, which take off in opposite directions. Each has an energy of 510 kev, which exactly balances the resting-mass energies of the annihilated positron and electron. Accordingly, when a high-energy gamma is absorbed by pair production, the end products are a moving electron and two 510-kev gamma rays which leave the scene of the annihilation in exactly opposite directions. In some of the scanning instruments ingenious use is made of this curious, 180-degree relationship.

When a body of scattering material is exposed to radiation, some of the incident photons go right through without interacting at all, and these reach the detector in their original, undegraded condition. This is less likely to occur when the material is either dense or thick, but it must be remembered that everything is, to some degree, transparent to gamma rays.

To sum up, when a radioisotope sends gamma rays outward through a patient's body, two important things happen: (1) some of the primary photons interact and are lost (*absorption*), and (2) secondary, lower-energy photons appear (*scattering*). Both these processes affect the number of gamma rays that reach an external detector. Absorption tends to reduce the count rate, but the scattering process can actually raise the rate, for it sends secondary rays flying off in all directions, and thus it can deflect into the detector some of the radiation that would otherwise have missed it. Here is one thing, then, that can disturb the proportionality between the amount of radioisotope and the count rate shown by a detector: the *disintegration rate* (microcuries) is wholly independent of the source's surrounding, but the *count rate* is not. Accordingly, if we want to measure an unknown source by comparing its count rate with that of a known standard,[4] we should arrange things so that the "counting situation" (absorption, scatter, size and distance) is the same for the standard and the unknown. This is easy to do if small samples are to be counted in a well counter, for example, but if the unknown activity is buried inside a patient the counting situation is out of control.

One way to get around this difficulty is to construct a "phantom" in which the known standard is always counted. For thyroid uptake we make a "neck phantom", so contrived that the absorption, scattering, size, and distance of the standard duplicate as closely as possible those of a radioiodine-containing thyroid gland situated in the usual position in a human neck. But human necks come in all sizes and shapes, and the thyroid

[3] A positron is a particle similar to the electron except that it carries a positive charge.

[4] When a measurement is made by counting the rays emanating from a radioactive source, the process is nearly always a relative one; the count from the unknown is compared with that obtained from a known standard. In medical work the standard is usually a known fraction of the dose given to the patient.

gland is likely to vary in shape and position, especially if there's something wrong with it. The phantom's job is therefore a tough one, and anything we can do to ease the strain is a step in the right direction. We can help by eliminating scatter from the picture, and since scattered gamma rays always have lower energies than their parents, they can be discriminated against if we can design a detecting system that refuses to count any gamma rays whose energies are substandard.

The medical spectrometer[5] is just such a *selective* gamma-ray detector – a device that can be made to see only the kind of gamma rays that the operator wants it to see. Though it does not work by resonance, it behaves, in effect, like a tuning circuit in a radio, which can let in the desired station but suppress all others. Thus the spectrometer can be set to receive the primary gamma-ray energy but disregard the scatter, and this provides a partial solution to the problem of counting radiation coming from a patient. Selective gamma counting also provides other important advantages, which will become clear, we hope, as the discussion proceeds. Some of these are mentioned in the conclusion, at the end of the handbook.

Any measuring process depends for its success on the collaboration of three basic components: (1) the method, (2) the instrument, and (3) the operator. The medical spectrometer will be used much more effectively if the operator has some idea of how his instrument works. Accordingly, let us inquire into its mechanism.

HOW A MEDICAL SPECTROMETER WORKS

Scintillation Crystal

As mentioned in the foregoing introduction, difficulties arise if gamma rays interact on their way out through a patient's tissues, for when this happens the radiation reaching the external detector will be altered in character and, in particular, will contain lower-energy components that were not present in the radiation originally given off by the disintegrating atoms. Thus, interactions within the patient are a nuisance. In the detector, however, interactions are a necessity, for it is only by observing the ionization phenomena that we are able to detect gamma radiation. The scintillation crystal is one of several devices that enable us to observe gamma-induced ionizations, and the medical spectrometer uses a crystal for its "seeing eye." Typically it is a 2-inch × 2-inch cylinder[6] of activated sodium iodide. In this heavy material most gamma photons of reasonable energy are stopped, and their energy is dissipated through the photoelectric and Compton interactions.

Sodium iodide, however, differs from ordinary absorbing materials in that flashes of visible light are emitted when the outer orbital electrons of the ionized atoms snap down into the vacant orbits. The light emitted by the recovering atoms lies in the blue, violet, and ultraviolet portions of the spectrum. This light can be used to activate a photoelectric cell and thus produce an electrical pulse, and by counting these pulses we can count the interacting gamma rays.

Pulse Height Measures Gamma Energy. – In a sodium iodide crystal of reasonable size there is a fair chance that all or nearly all of an incoming gamma ray's energy will be deposited in the crystal. With gamma rays of medium energy (a few hundred kev) there is a high probability that the first interaction will be of the Compton type, for the photoelectric process is predominant only when the energy is low. Accordingly, the incoming photon can be imagined as blasting an inner-shell electron out of one of the iodine atoms but not transferring all its energy to the electron, so that there remains a secondary gamma photon, of energy lower than the primary. The secondary photon shoots off at an angle and, very likely, interacts with another iodine atom, producing a second electron and another scattered gamma, with energy

[5] This term was first used to describe a new pulse-height spectrometer, designed by Francis, Bell, and Harris of the Oak Ridge National Laboratory with the express purpose of providing for clinical needs ("Medical Scintillation Spectrometry": Nucleonics 13, No. 11, pp. 82–88, 1955). In a way, the name should really be restricted to their design, but since the publication of the Francis-Bell circuit, various manufacturers have brought out clinically oriented spectrometers, some copied faithfully from the ORNL specifications, others containing minor modifications, and still others using pretty obviously different circuitry intended to achieve the same ends by supposedly better means. The meaning of "medical spectrometer" is therefore in the process of shifting from one specific instrument to a family of instruments all beamed at clinical needs. The present account concerns itself with the Francis-Bell design, although the basic principles apply to a broad group of instruments.

[6] Crystal dimensions must be decided by engineering compromise, and opinions differ as to the best size for general purposes. Large crystals catch more gamma rays and are therefore more efficient, especially if the energy of the radiation is high. But the high sensitivity provided by a large crystal carries with it a need for thicker shielding (in order to keep the background low) and this makes the detecting head inconveniently bulky and heavy, and necessitates more costly supporting equipment. Accordingly, some sort of compromise is inevitable.

still further degraded. The process is repeated (Fig. 1, left) until the energy of the scattered photon has sunk so low that a photoelectric interaction finally occurs, in which the photon vanishes and the photoelectron carries away all the remaining energy. As mentioned before, all the dislodged electrons, traveling at high speed, produce ionizations of their own. With this picture in mind, then, we can see that the more energetic the incident photon is, the greater will be the number of ionized atoms and therefore the more intense the scintillation. In fact, unless some of the dislodged electrons or scattered photons manage to escape from the crystal without contributing their share of ionizations (see Fig. 1, "partial absorption"), the intensity of the scintillation will be proportional to the energy of the incoming gamma photon, and therefore we can measure the energy of the gamma ray by measuring the intensity of the scintillation.

This is what a pulse-height spectrometer does. A photoelectric tube is attached to the scintillation crystal in such a way that it can inspect each flash and generate an electrical pulse whose height is proportional to the intensity of the scintillation, and therefore proportional to the energy delivered by the gamma ray to the crystal (Fig. 2). The electrical pulses then can be counted, but with the help of some basically simple electronic trickery we can arrange to count only those pulses whose heights fall within a selected range determined by dial settings. In this way the pulses representing a narrow band of gamma energies are counted, while all others are ignored. This enables us, if we set the dials intelligently, to count whatever band of gamma energies we like. In addition, many of the usual background pulses will be ignored because they fall outside the selected range, and thus the ratio of count to background improves.

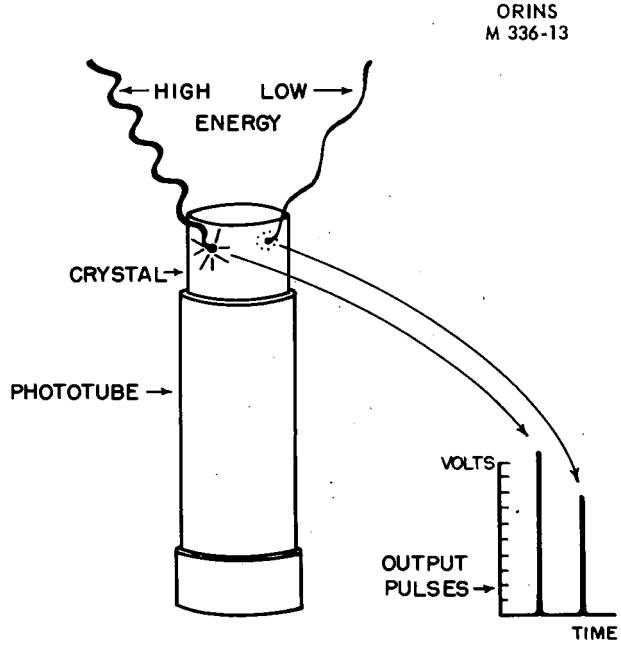

Fig. 2. With Careful Design, Pulse Voltage Measures Gamma Energy.

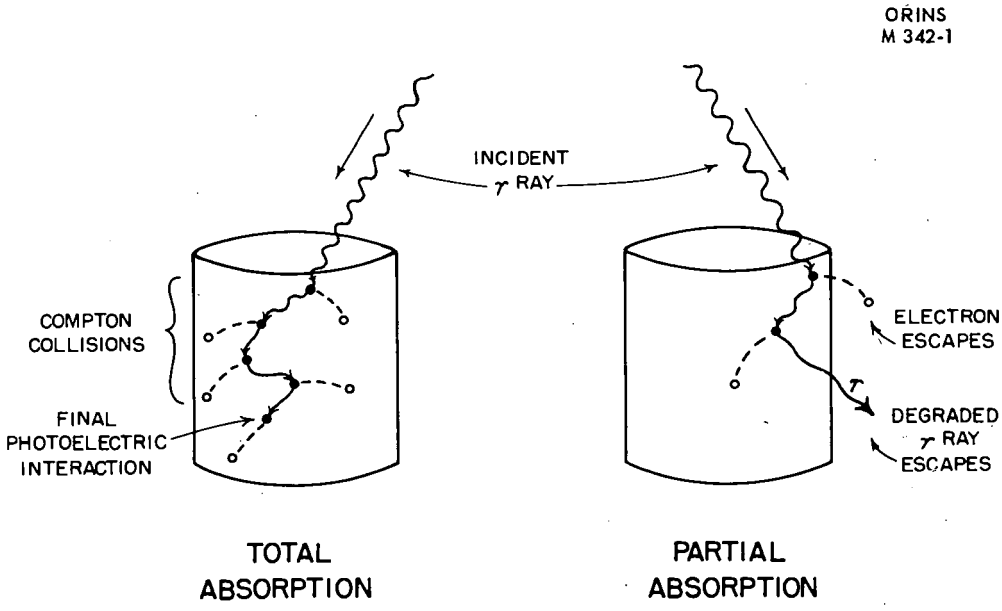

Fig. 1. Total Absorption, and Escape Phenomena, in a Scintillation Crystal.

A spectrometer also permits us to plot the gamma-energy spectrum of an emitting material by counting individually the various bands of pulse heights. Each radioisotope has a characteristic spectrum of its own (a kind of finger-print pattern), and so the spectrum can be used to establish the identity of an unknown or uncertain source. Suppose that a radioactive accident happens, for example, and a patient is brought in "hot"; it is of the utmost importance to find out what the contaminating isotope is, and the history of the accident will not always provide the answer. A gamma-energy spectrum usually will.

Limitations Inherent in Scintillation Spectrometry. – A good-sized crystal does a pretty fair job of producing a scintillation whose intensity is proportional to the energy of the incident gamma ray, but as mentioned a moment ago, every so often a gamma ray will fail to expend all its energy in the crystal (Fig. 1), in which case the pulse produced by the phototube will not be as tall as it should be, since the scintillation represents only part of the incoming energy rather than the whole of it. These "partial interactions," as they are called, cause the pulse-height spectrum to present an exaggerated picture of the low-energy content of the incident radiation, and in this sense a pulse-height spectrometer distorts the true gamma spectrum. There are, of course, ways of keeping the percentage of partial interactions down to a minimum. Clearly there will be more of them if the crystal is small, for this will increase the probability that an ejected electron or a scattered photon will escape scot free. Again, partial interaction is favored if the incident ray enters the crystal near one edge, or at an angle such that it tends to cut through a corner. It is easy to understand, accordingly, that a pulse-height spectrum will more truly represent the constitution of the incoming radiation (1) if the crystal is three or more half layers thick, (2) if its receiving area is reasonably large, thus providing a low edge-to-interior ratio, and (3) if corner-cutting is discouraged by having the source either right up against the crystal face or else backed off a fair distance, with the intermediate positions providing more prominent escape phenomena. As one would expect, the higher the energy of the radiation to be detected, the larger the crystal will need to be in order to keep out of trouble.

In addition to the gamma rays that react only partially, there will be some that go right through the crystal without interacting at all. These will not distort the spectrum, for if they leave no telltale ions the detector remains blissfully unaware of their existence. We cannot tolerate too many of these undetected gamma rays, or the efficiency of the detector will droop down to an impractical level. Here again a thick crystal is helpful, for it will provide a high percentage of completely reacting gammas, a low percentage of partial energy transfers, and a still lower percentage of clean misses.[7] It is a pity that large crystals are so expensive, so inconveniently bulky, and so awkward to shield and collimate effectively.

It will be gathered from the foregoing discussion that a gamma-ray spectrum as obtained from a pulse-height spectrometer will inevitably suffer from some degree of distortion; part of this distortion will arise within the instrument – as a result of partial interactions and what not – and accordingly we can call this the instrumental component. We must also remember, however, that the radiation reaching the detector has already been distorted by the absorption and scattering that always occurs, in greater or lesser degree, while the radiation is travelling from the disintegrating atom to the detector. The spectrometer can hardly be blamed for this "predetector" distortion, since it depends on what surrounds the radioactive source and what lies between the source and the detector. People who work with pulse-height spectra must simply learn to interpret them with intelligence and insight, constantly bearing in mind the sources of predetector and instrumental distortion. Readers interested in this subject will do well to consult more detailed accounts, such as the chapter by P. R. Bell on "The Scintillation Method" (page 133 and following) in Siegbahn's Beta- and Gamma-Ray Spectroscopy"; New York, Interscience Publishers, 1955.

While we are talking about scintillation crystals we might point out that although the *quantity* of light in the scintillation depends on the amount of energy the gamma ray transfers to the crystal, the *quality* of the light ("color" if you like) depends on the material of the crystal and not on the kind

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[7] $\frac{\text{photons reacting completely}}{\text{total incident photons}}$ = "intrinsic peak efficiency";

$\frac{\text{photons reacting in any fashion}}{\text{total incident photons}}$ = "total efficiency."

of radiation. In sodium iodide the iodine provides most of the stopping power (since it has a high Z number), and it is the resettling of the iodine's orbital electrons that produces the blue, violet, and ultraviolet light of the scintillation. The crystal fortunately transmits this kind of light well, and thus the scintillation can be seen and measured by the adjoining phototube. A sodium-iodide crystal may tend in time to become discolored, in which case some of its scintillation light is absorbed before it reaches the phototube, and the electrical pulses are reduced in size. If the discoloration is spotty, only some of the pulses are smaller, while others remain of nearly standard size, and in this case the proportionality between pulse height and gamma energy deteriorates.

It will be recognized from what has been said that a "scintillation" is in reality a very brief shower of minute flashes, each flash resulting from the resettlement of the electrons in an ionized atom. The flashes occur randomly in time, but they are more closely spaced in the early portion of the scintillation, and less so toward the end. In a sodium-iodide crystal the whole process is completed in one or two millionths of a second, so that to the naked eye the shower looks like a single flash. Figure 3 shows a much-spread-out version of the initial portion of the electrical pulse, and it is seen that each little flash produces a small step of its own.

The Crystal-Phototube Unit

Whatever the size of the crystal, we must arrange it so that a photosensitive device of some sort can see the scintillation and tell us how bright it is. We therefore cement the crystal to the sensitive end of the photomultiplier tube, whose action will be explained in a moment (Fig. 4). We must use a cement that transmits violet light well and provides good optical continuity between the crystal and the glass of the tube, so that almost no light will reflect back into the crystal. Heavy mineral oil works well, and so do some of the higher silicone oils. Care must be taken to exclude all air bubbles, which would provide reflecting surfaces. This "exit surface" of the crystal is, however, the only one where we want the light to get out; at all the other surfaces it should reflect, so that it will not escape and be wasted; therefore we rough-grind these other

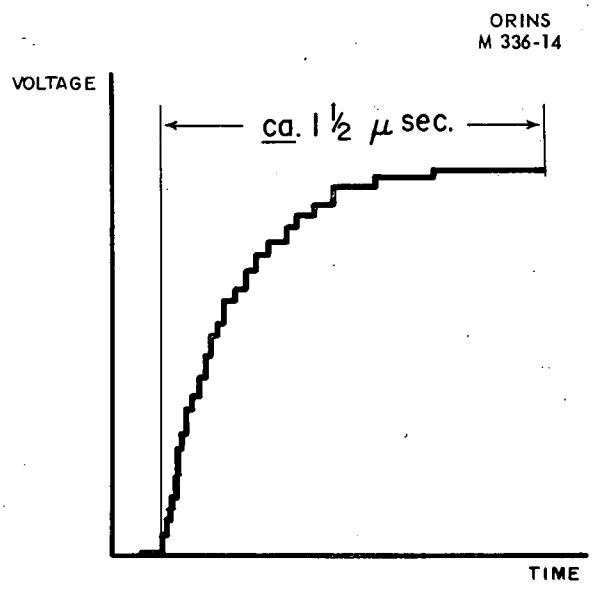

Fig. 3. The Rising Portion ("Step") of the Electrical Pulse, Showing Numerous Small Steps.

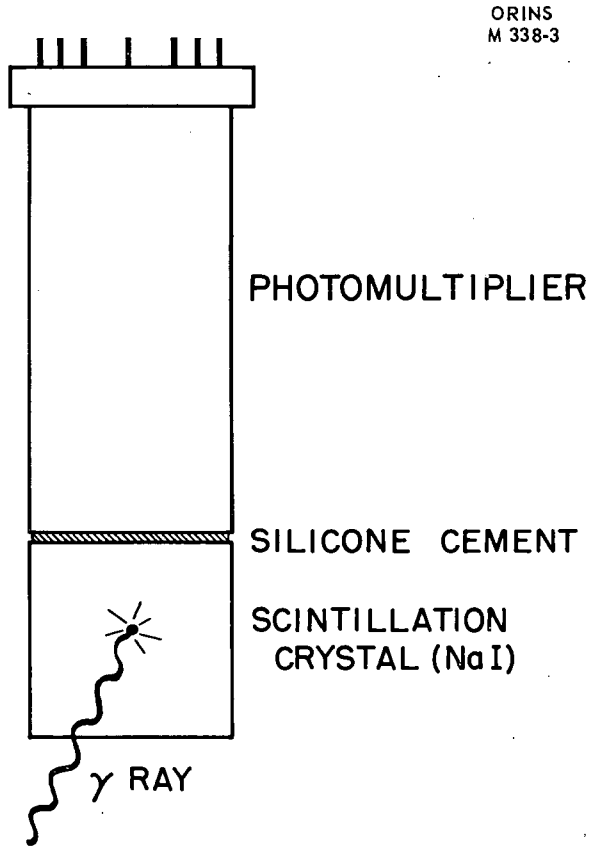

Fig. 4. Crystal and Photomultiplier Assembly.

surfaces and coat them with a brilliantly white powder such as aluminum oxide. The crystal-and-phototube assembly is then encased in a thin, aluminum can, which lets gamma rays in easily but excludes room light. The can must also keep water vapor away from the sodium iodide, which is deplorably hygroscopic. Commercial crystals are often canned separately, with the exit surface protected from the air by a transparent window, and the latter can be sealed to the phototube.

The visible and ultraviolet light generated by the scintillation process enters the end of the phototube and strikes a structure called the photocathode, which is a very thin layer of a cesium-antimony compound deposited on the inside of the phototube's end window. The photocathode emits free electrons under the action of light. Located near it is the first of a series of structures called dynodes (Fig. 5). The first dynode is given a potential about 100 volts more positive than the photocathode, and each of the other dynodes is about 100 volts more positive than the one before it.[8] With this arrangement there is a strong electrostatic field that promptly pulls the liberated electrons away from the photocathode and accelerates them toward the first dynode, which they strike so forcibly that other electrons are splashed out of its surface. Here, however, there is a new electrostatic field that pulls them toward the second dynode, where they strike and splash again. This is the process of electron multiplication; at each dynode the number of departing electrons is 3 to 5 times the number that arrived, and the amplification achieved by a string of 10 dynodes can therefore be enormous (for example $4^{10} \doteq 1$ million). Beyond the final dynode there is a still more positive collecting plate, and the arrival of the cloud of electrons at the plate produces a pulse that can be amplified and counted.

[8] In the interests of simplicity, I am taking considerable liberty with these voltage figures.

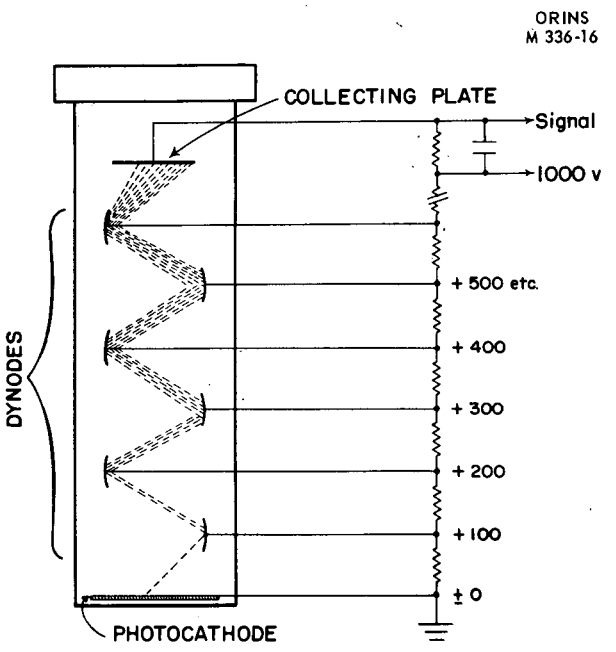

Fig. 5. Electron Multiplication in the Phototube.

The violence of the "splash" at the surface of a dynode depends upon how fast the electrons are traveling when they strike, and this depends in turn on the strength of the electrostatic field responsible for accelerating them. The amount of splashing, and hence the amount of electron multiplication (or "gain") is therefore dependent on the voltage difference between dynodes, and in fact the gain is roughly proportional to this voltage difference. The dynodes derive their potentials from a string of voltage-dividing resistors (Fig. 5) whose high end is connected to a d-c voltage supply. If the high voltage should increase by 1 per cent, the voltage on each dynode will increase by about 1 per cent, and therefore the electron gain at *each* stage will also increase by about 1 per cent. This means that the over-all gain will increase by something like 10 per cent (since $1.01^{10} = 1.10$, approximately), and this is why the high-voltage supply of a medical spectrometer must be very carefully stabilized if constant gain is to be maintained. Stable gain is important because the pulses are to be accepted or rejected, farther down the line, on the basis of pulse height. In a pulse-height spectrometer, then, the demands on the high-voltage supply are particularly exacting, and special care must be taken to keep the high voltage constant. The spectrometer's long warm-up time (an hour or more) is needed mainly in order to permit the stabilizing circuits to reach temperature equilibrium, and this is one reason why we recommend that unless the instrument is to be used only occasionally it should not be turned off.

At this stage of the game the scintillation in the detecting crystal has been made to produce an electrical pulse, but the pulse height will not measure gamma energy unless we take certain precautions in designing the photomultiplier's output circuit. The basic process involved in the

generation of the electrical signal is the sudden arrival of a cloud of electrons at the collecting plate. If the plate is kept charged at +1000 volts or so by having it connected directly to the "hot" side of the high-voltage supply, electrons landing on it will be rapidly whisked away into the high-voltage supply, and this would give us a very brief pulse of current flowing in the plate's lead wire. What we want, however, is a *voltage* pulse, and one way to make a voltage signal out of a current is to pass the current through a resistor. Such an arrangement is shown in Fig. 6, and with this circuit the arrival of the cloud of electrons at the plate will generate a voltage pulse that can be led off to the amplifying system.

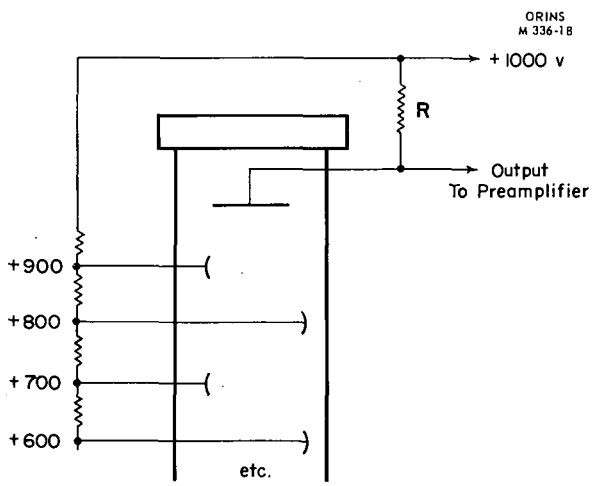

Fig. 6. Output Circuit for Simple Pulse Counting.

This design is satisfactory enough if all the operator wants to do is to count the *number* of scintillations, without concerning himself about whether they are strong or weak. A little thought will show us, however, that the simple resistor will not be good enough if pulse height is to measure gamma energy. Since the resistor is making voltage out of the current pulse, the peak voltage will indicate the maximum *current*, and thus the pulse height tells us only *how fast* the electrons were arriving, at the particular instant when they were coming in most rapidly. But we don't happen to care about their rate of arrival; what we need to know is *how many* there are in the whole cloud, because this number divided by a million (for example) tells us how many electrons were dislodged from the photocathode, which is a measure of the intensity of the scintillation, which is proportional, approximately, to the energy of the gamma photon. Accordingly, we need a circuit that simply adds up all the electrons in the cloud collected by the plate, and doesn't care about how fast they arrive.

Such a process of addition – the mathematicians prefer the more lofty term "integration" – can be achieved readily by letting the electrons charge up a condenser. Condensers follow the law: $Q = CV$, or $V = \frac{Q}{C}$, where V is the voltage between the condenser's plate, C is the capacity, and Q is the impressed charge, which simply means the number of electrons pushed into the condenser.[9]

In everyday language, the equation tells us that the voltage between the plates of a condenser is proportional to the charge, so the voltage can be used as a measure of the number of electrons in the charge. Taking advantage of this property, we insert a condenser into the phototube's plate lead (Fig. 7) and, as before, take the output pulse from the plate. With this arrangement whenever a cloud of electrons arrives, the plate potential takes a negative jump, and the size of the jump or "step" is a measure of the number of electrons. In this way the step voltage measures gamma energy, which is what we want it to do.

If we had nothing but the condenser in series with the phototube's collecting plate, the incoming electrons could not get away, and would soon reduce the plate's voltage to a level at which the

[9] Charge is ordinarily measured in coulombs, one coulomb being equal to 6¼ billion billion electrons (6.242×10^{18}).

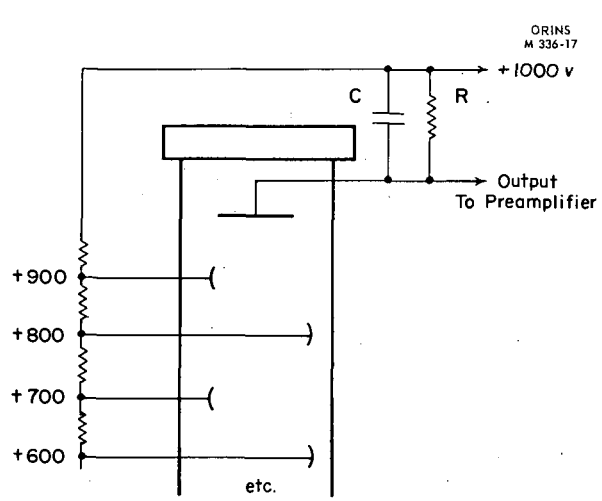

Fig. 7. For Pulse-Height Analysis, an "Integrating Condenser" Is Added at the Output.

tube would no longer function; so we must provide a leak to allow them to drain off into the high-voltage supply and thus return the plate to its original positive potential. This is the purpose of the resistor placed in parallel with the condenser (Fig. 7). The leak must not be too rapid, of course, for this would let too many electrons drain away during the charging process; but if we proportion the resistance and capacity correctly, the step voltage, which occupies only a millionth of a second or so, will be completed before any appreciable part of the charge is lost.

The actual circuit in the medical spectrometer is not quite as simple as this, but the principle is the same: a capacity is charged rapidly by the oncoming burst of electrons, after which equilibrium is re-established, with leisurely dignity, by strategically placed resistive leaks. Recovery is about 63 per cent complete in 200 microseconds; for full recovery, of course, the circuit theoretically needs infinite time. Thus for a single gamma photon, the wave form at the photomultiplier's output looks something like that of Fig. 8: a very rapid "step," (Fig. 3) followed by a long "tail." As we shall see in a moment, the spectrometer soon converts this step pulse into a brief, square wave (reasonably square, that is) whose height is the height of the step.

Conventionally a photomultiplier's output pulse is taken from the collecting plate, in which case the pulse is negative in polarity. In the medical spectrometer, a negative pulse from the phototube would complicate the problems involved in the design of the subsequent amplifier, and so a subterfuge is used: the photomultiplier's pulse is obtained not from the plate but from the final dynode, where it is positive. The pulses are positive at the dynodes because more electrons leave a dynode than arrive, while at the plate the pulse is negative because electrons arrive but do not bounce off. The use of the final dynode to provide the output signal does not alter the phototube's basic mechanism; it involves some sacrifice in gain, of course, but this is made up again in the amplifier. With the high-voltage settings commonly used, the gain in the photomultiplier is typically somewhere around 100,000.

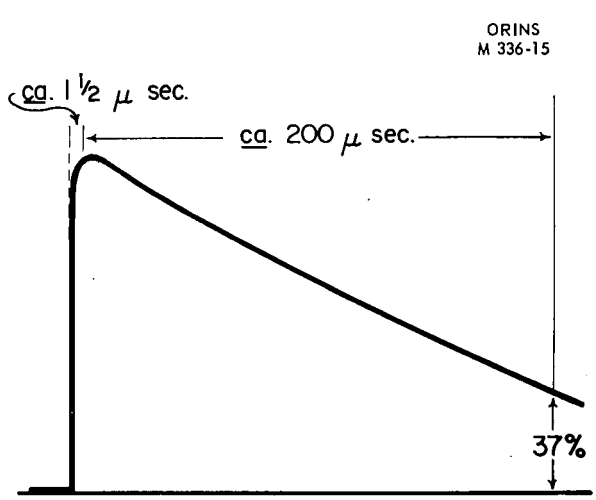

Fig. 8. Photomultiplier Output Pulse, Showing Very Fast Rise ("Step") and More Leisurely Recovery ("Tail").

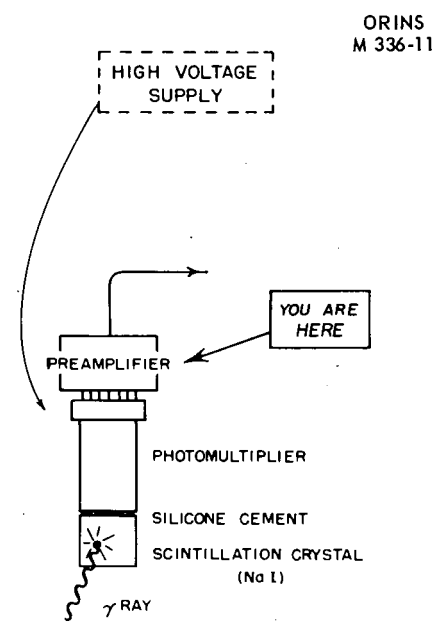

Fig. 9. Components in Detector Assembly.

Preamplifier

In the rear end of the medical spectrometer's detector assembly there is a single vacuum tube connected as a cathode follower. This tube is called a "preamplifier," but actually it doesn't amplify the pulse at all; it merely provides a driving source whose characteristics are such that the pulse will not be lost in the several feet of cable connecting the detector to the main spectrometer chassis. The cathode follower also helps to provide a substantially constant impedance from which the delay line, to be described in a moment, will be driven. At any rate, the step pulses produced through the action of the crystal and photomultiplier are delivered through the

interconnecting cable to the input of the linear amplifier in the main spectrometer chassis.

Delay Line and "Pulse Shaping"

The step pulses are still in the form shown in Fig. 8, consisting of a quick rise to maximum followed by a slowly declining tail. This shape is unsatisfactory for pulse-height analysis because a second pulse, arriving very shortly after the first, could stand on the tail left by its predecessor and therefore appear taller than it really is. This difficulty is resolved through the action of the *delay line*, whose job it is, roughly speaking, to convert the step pulse into a square wave of very brief duration; and since the square wave has no tail, another pulse can follow it closely without deceiving the pulse-height circuits.

When the preamplifier's output pulse arrives at the main spectrometer chassis, the first thing it encounters is the delay line (Fig. 10). This consists of a long, grounded sleeve in the center of which is an insulated, very fine coil of wire. At the far end of the line the coil is carefully soldered to the sleeve, thus short-circuiting the free end. The interplay between inductance and capacity in the line is such that the pulse runs down to the far end and then bounces back, much as a shout echoes back at the speaker from a cliff. With proper design the reflected pulse returns to the starting point equal to the original pulse in magnitude but opposite in polarity, and it is about *1 microsecond late*. Thus when the original and the reflected pulses add together algebraically, the original step is retained but, 1 microsecond later, the tail is canceled out, leaving a substantially flat base line ready for the next pulse.

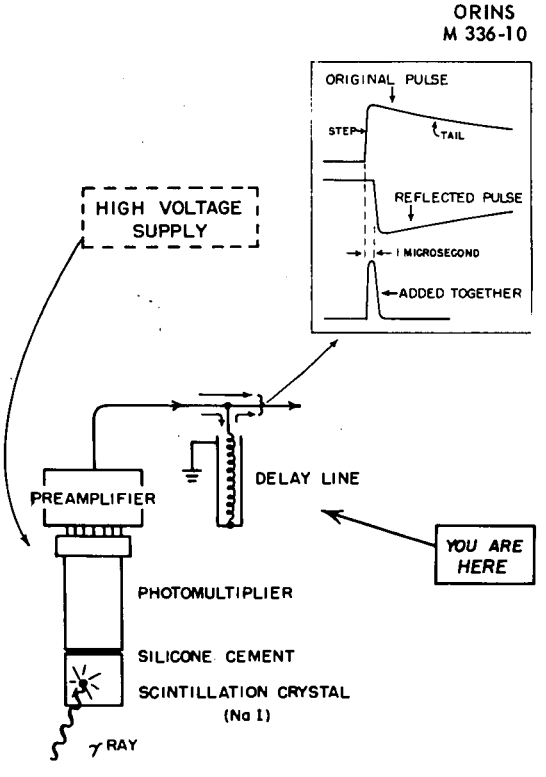

Fig. 10. Delay Line.

The action of the delay line is shown pictorially in the insert of Fig. 11. The one-microsecond pulses produced are, of course, not precisely square, for the original step pulse rises sharply but not instantaneously (see Fig. 3). Nevertheless, the final product of the pulse-shaping process is a reasonably serviceable, very brief pulse whose height is proportional to the energy of the gamma ray that produced it; and after amplification, these pulses can be sorted effectively by the selecting circuits to be discussed in a later section.

It should be pointed out that in order to achieve accurate cancellation of the tails on the step pulses, the parts of the circuit associated with the delay line have to be rather carefully adjusted at the factory, for otherwise some portion of the tail, either positive or negative in sign, is likely to persist. Accordingly if the detecting head of one medical spectrometer is transferred to another chassis, there is no guarantee that delay line number 2 will work properly with detector number 1, since part of the delay line's driving circuit resides in the preamplifier. He who switches detectors, therefore, does so at his own peril, and he who replaces a spectrometer's own detector with one designed for a different instrument commits a mortal sin.

Linear Amplifier

The pulses derived from the medical spectrometer's sensing head are typically only a few millivolts in height, which means that they must be amplified considerably in order to permit the sorting circuits to do their job with any kind of precision. Accordingly, the pulses leaving the delay line are fed into an amplifier (Fig. 11). It is usually called a "linear amplifier" because special care is taken to see that the magnitude of an output pulse is closely proportional to that of the input pulse producing it. The amplifier consists of four tubes in two successive sections,

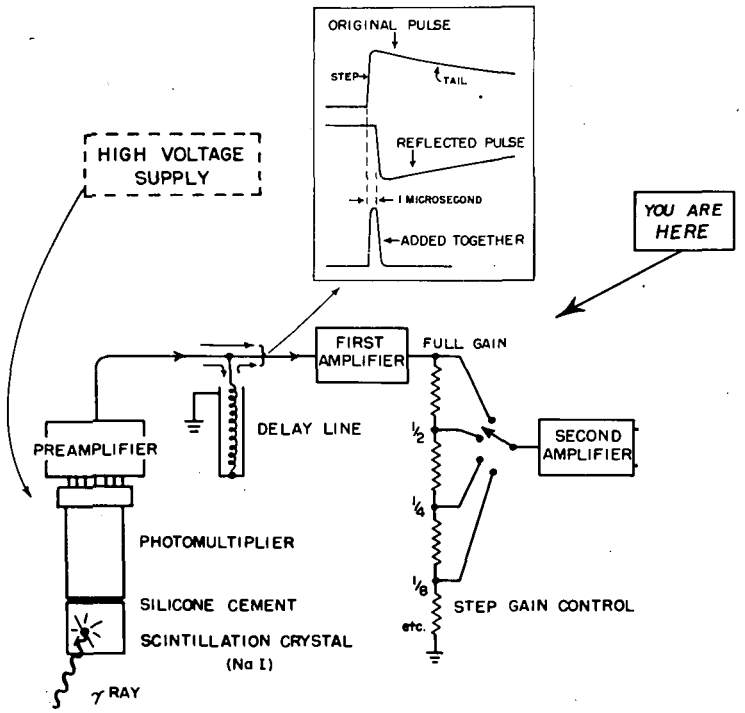

Fig. 11. Two-Section Linear Amplifier, with Step Gain Control Between Sections.

and each section is provided with negative feedback in order to stabilize the gain and promote good linearity. The voltage gains for the two sections are 70 and 120, approximately, so that the over-all amplification is something better than 8,000. Roughly speaking then, if the amplifier receives millivolts at its input there will be tens of volts at its output, and it can deliver 100 volts or more with negligible distortion. Moreover, it recovers quickly after overload – that is, after receiving an input pulse too big to be amplified linearly. This is helpful because large pulses are bound to come along from time to time – for instance whenever a cosmic or other high-energy ray hits the crystal. Amplifiers in general are inclined to sulk for a while if you poke them too hard, but this one overloads without resentment.

Between the two sections of this amplifier there is a step gain control (Fig. 11), with which the operator can cut down the amplification successively in ratios of 1:2. Thus the five steps on the gain control represent full gain, one-half, one-quarter, one-eighth, and one-sixteenth of maximum gain. These switch positions are represented on the front panel by the numbers: 32, 16, 8, 4, and 2, the figures suggesting that at each step the amplification is half that of the next higher step. We should note in passing that the gain ratios are not intended to be mathematically precise, since there is no real need for this, and the voltage divider is constructed of 5-per-cent resistors.

Pulse-Height Analyzer[10]

The pulses have now been blown up to a workable size and are ready to be presented to the portion of the circuit that decides which are to be counted and which rejected. Each pulse reaches its maximum voltage in about a millionth of a second, and for the reasons discussed previously this peak voltage or "pulse height" is a measure of the energy of the gamma photon that produced the pulse. Accordingly, when we sort out these pulses in terms of height, we are doing the equivalent of sorting the gamma rays according to their energies, and as mentioned in the introduction, we would like to be able to pick out the gamma rays representing the primary emission of the radioisotope in question and disregard all others whose energies lie either higher or lower than the

[10] Sometimes called a "kicksorter."

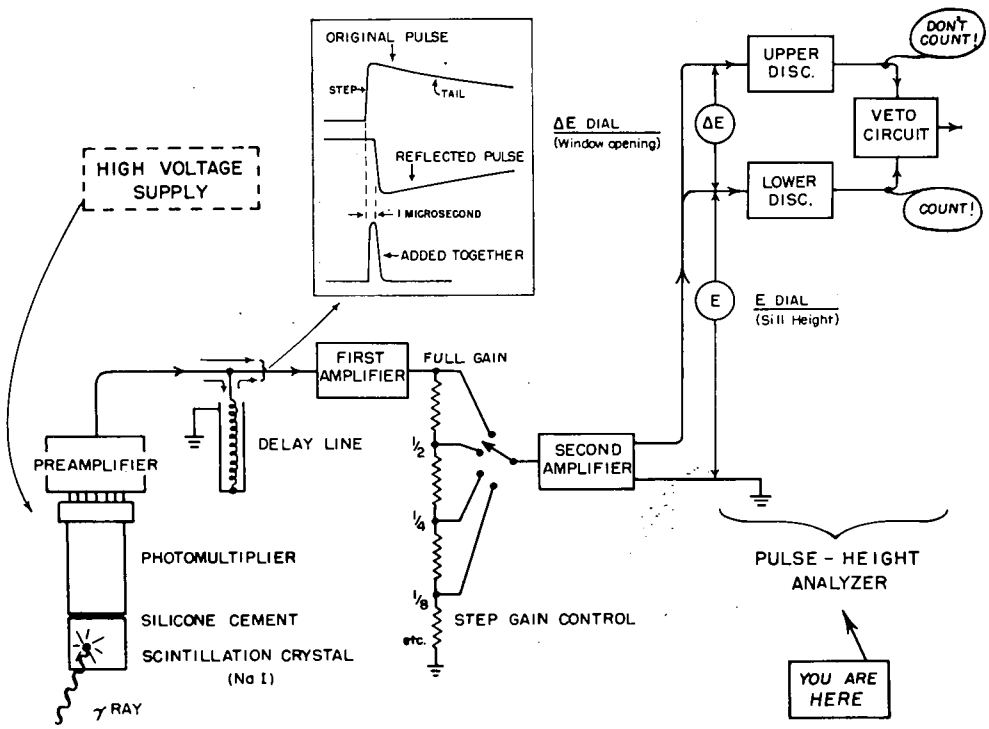

Fig. 12. Pulse-Height Analyzer, or "Electronic Window."

primary energy band. In fact, we would like to be able to pick out *any* group of gamma rays at will, whether primary or scattered, and count them.

It may be helpful to digress for a moment and consider an analogy. Suppose we have a large herd of giraffes and we are interested in finding out how tall they are: how many fall into the 12-foot category, how many in the 11-foot, 10-foot, and so on. We might do this by driving them in single file past a high window, stationing an observer well back inside the room, looking out of the window, and instructing him to count all giraffes whose ears he could see, but no others. This procedure would tell us how many giraffes there were in a given height category. If we became interested in other categories we could move the window-and-observer up or down, and count again. We could make the categories as coarse or as fine as we pleased by opening up the window widely (say an 8-foot sill and a 12-foot top) or by closing it down to a narrow slit (for example 12 feet to 12 feet 6 inches).

A pulse-height analyzer operates on this same basic principle. If we want to count all pulses whose peaks lie between 60 and 70 volts, we build ourselves a kind of electronic window provided with controls so that we can set the window sill at 60 volts and then adjust the window itself for a 10-volt opening. This window, according to our "instructions," will ignore all pulses whose peaks are higher than 70 volts or lower than 60. The 10-volt band of pulses will correspond, of course, to a certain energy band among the gamma rays that strike the scintillation crystal; therefore by moving the electronic window up and down we can, within reason, select any group of gamma energies in which we may be interested. If we want to cover a wide band of energies we make the spacing between window sill and top large; if we want to confine our attention to a small energy band, we can reduce the window opening so that the sill and top are close together.

In a giraffe-counting experiment we would be likely to find one particular window level at which the largest number of giraffes would be seen, while above and below this "most densely populated" height category the numbers would be smaller. We find the same kind of thing when we look at the pulse heights: for a given gamma energy there is a "mode," corresponding to the

most-frequently-occurring height, and on either side of this the frequency falls off in more or less bell-shaped fashion (Fig. 16), some pulses being taller and others shorter than the "most probable." This dispersion should not surprise us, for we can think of several factors that would contribute to it. We have considered one of them already, namely the occasional escape of some of the gamma energy to regions outside of the crystal (Fig. 1). But not only do a few electrons and scattered photons escape, some of the visible light also does, although we minimize this by coating the crystal with a white, reflecting powder on all surfaces except the one leading to the phototube. Perhaps not much of the light actually escapes, but some of it must reflect several times, with a small loss each time, before finding the photocathode, and of course with many reflections there is a longer pathway, causing increased absorption in the substance of the crystal itself. It is understandable, accordingly, that for the same scintillation intensity we do not always get the same number of electrons released from the photocathode. Furthermore, many scintillations are so weak that they release only a dozen or so electrons from the photocathode anyway, and with small numbers of this kind there will inevitably be statistical variations between the effects of one scintillation and another of the same brightness. Still another factor is that the scintillations are produced at different places, and it is likely that the photocathode does not see all portions of the crystal equally well.[11] Again, we can never make the photocathode completely uniform in sensitivity throughout its whole area, for it is deposited on the inside surface of the phototube's glass envelope at one end, and the thickness of the layer is bound to vary a little from one region to another. If the scintillation occurs near a high-sensitivity area, the pulse will be taller than it would be if the flash is seen mainly by an area of low sensitivity. There are still other effects tending to produce dispersion of the pulse heights: minor vagaries of electron behavior as they jump from dynode to dynode, "dark noise" in the phototube, hum and other electrical noise in the amplifier, and so forth. Interested readers should consult larger works for further details (see Siegbahn reference).

[11] This is especially true in a "well crystal," which contains a central hole for the insertion of a small samples in a test tube. Here the hole casts shadows on the photocathode, and the dispersion is unusually severe.

In short, we must candidly admit that the proportional relationship between pulse height and gamma energy suffers from a certain amount of looseness in its joints; it holds in a statistical sense, but it is not precisely true for each individual pulse.

The electronic gadgetry that gives us the window mechanism is interesting and ingenious. Here we will examine only its basic principles, being careful not to get bogged down in the details of the circuitry. The fundamental electronic element is the "discriminator," or "threshold circuit," which will be "triggered" only if the input voltage reaches or surpasses a certain critical level, whereas short of that point it will remain quiescent. Its behavior may be compared with that of the toggle switch that turns on the instrument's power; we can move the *lever* of this switch to any desired position between the two extremes, but *electrically* the switch will wait until the critical position is reached, and then will flip on suddenly. Furthermore, the switch will respond either completely or not at all, with no in-between stages. Similarly the discriminator circuit completely ignores any incoming pulse that is too small, whereas if the pulse reaches or exceeds the threshold voltage the circuit will fire vigorously.[12]

It is fairly easy to provide a threshold circuit that will give us the window sill; it is not quite so easy to put a top on the window. Going back to the giraffe analogy, we may imagine that the observer we have posted inside the window is rather stupid; he can be trusted to shout, "Count!" if he sees a giraffe's ear, but we can't trust him to keep quiet if he sees the neck but not the ears. To get around this difficulty we employ two stupid observers instead of one. Each of them operates on a simple window-sill basis: each is instructed to shout if he sees *any* part of a giraffe. But we give the two observers separate window sills to sight over, one higher than the other. The Lower Observer is given (for example) a "60-volt" window sill and is instructed to shout, "Count!" whenever he sees a piece of a giraffe. The Upper Observer, on the other hand, might have a "70-volt" window sill, and he also is to shout if he sees any part of a giraffe. The checker who makes the final tally discards all giraffes seen by the Upper Observer, who is thus given a kind of veto power over the Lower Observer. Under this policy

[12] Readers acquainted with elementary physiology will recognize here the first cousin of an old enemy: the "all-or-nothing" law of nerve and muscle.

the only giraffes counted will be those tall enough to be seen by the Lower Observer but not so tall that they are seen by the Upper Observer, and thus we achieve the effect of a window with both sill and a top by employing two simple-minded window-sill mechanisms with an appropriate difference in level between them.

With these considerations in mind we may take a look at the electrical design, as shown schematically in Fig. 12. First we construct a discriminator circuit that will fire if the top of the oncoming pulse rises above a selected threshold level. Next we build into the circuit whatever embellishments are necessary to make the threshold adjustable (E dial.) We use this circuit to represent the window sill and, if we want to follow engineering terminology, we call it the "lower discriminator." We then build another similar circuit to represent the window top, and we call it the "upper discriminator." We feed the outputs of the discriminator circuits into a mixing device so contrived that it will give the upper discriminator veto power over the lower, and this will allow a "count" pulse to pass along to the scaler only if the lower discriminator is triggered alone, and not if the upper discriminator also fires. The scaler therefore counts only those pulses falling within a selected pulse-height range or, in simple terms, only those pulses whose peaks can be seen through a hypothetical "window" whose sill height and opening we can adjust.

Please note that the two adjustments are to be for *sill height* and *window opening*; we do not make the level of the window top independently adjustable. Thus when the sill elevation is changed the top will move with the sill, maintaining the same spacing between the two. There are several good reasons for preferring this arrangement. Perhaps the most important is that in order to calibrate the instrument so that we will know what band of gamma energies it is counting, we must be able to sweep the window up and down to search out the position of maximum count rate for an incoming gamma ray of known energy – for example chromium-51 or cesium-137 (Fig. 16). This is easy if the window top moves with the sill, but it would be a frightful nuisance if, every time we change the sill, we had to stop and figure out where we should put the top in order to give the same opening as before.

The engineers use an ingenious dodge to keep the window opening independent of the sill height, and it merits a short digression. The threshold circuit used for the sill is like the fence around a ball park: if you're tall enough you can see over it (if you're a giraffe, for example!), but if you aren't, you can't – unless, perhaps, you can find a box to stand on. The medical spectrometer's designers have elected to set their window-sill fence at a high level (about +100 volts) and keep it there, and if they want a short pulse to be accepted they give it an electrical "box" to stand on – that is, they let it start not from zero volts but from some positive level, such as 40 volts, for example. If we provide a 100-volt fence and a 40-volt box, then you will be able to see over the fence if you are a 60-volt pulse, whereas without the box you would have to be 100 volts tall (Fig. 13). The height of the electrical "box" is adjustable (E dial,) and this is what determines the minimum height that a pulse must have in order to fire the lower discriminator.

The sill circuit is locked at the 100-volt level, and never moves; the window-top circuit works similarly, except that its level is adjustable between 100 and 110 volts (ΔE dial). Suppose the window is wide open, so that the window top is at 110 volts (Fig. 14-a). If there is no "box", a pulse will get through only if its peak lies between 100 and 110 volts. In engineering terminology there is a 10-volt "pass band." If we now adjust the E dial so that the base line ("box") comes up to +40 volts (Fig. 14-b), the pulses in order to get through must have heights lying

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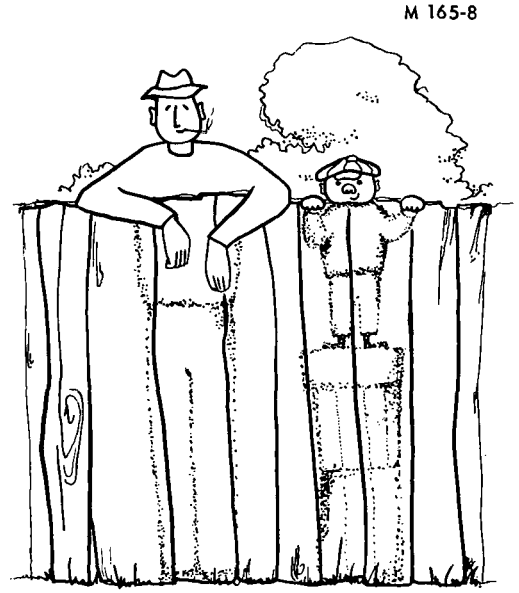

Fig. 13. You Can See into the Ball Park If You Have a Box To Stand On.

between 60 and 70 volts; we haven't changed the width of the pass band because we didn't move the levels of either the sill or the top. Now if we readjust the ΔE dial (window opening) so that the window top comes down to 105 volts (Fig. 14-c), the pass band will lie between 60 and 65 volts. We have narrowed the window opening without changing the height of the sill because the electrical "box" (E dial) was left alone. This is how the two dials are made independent; the E dial (sill height) does not change the window opening, and the ΔE dial doesn't change the sill height.

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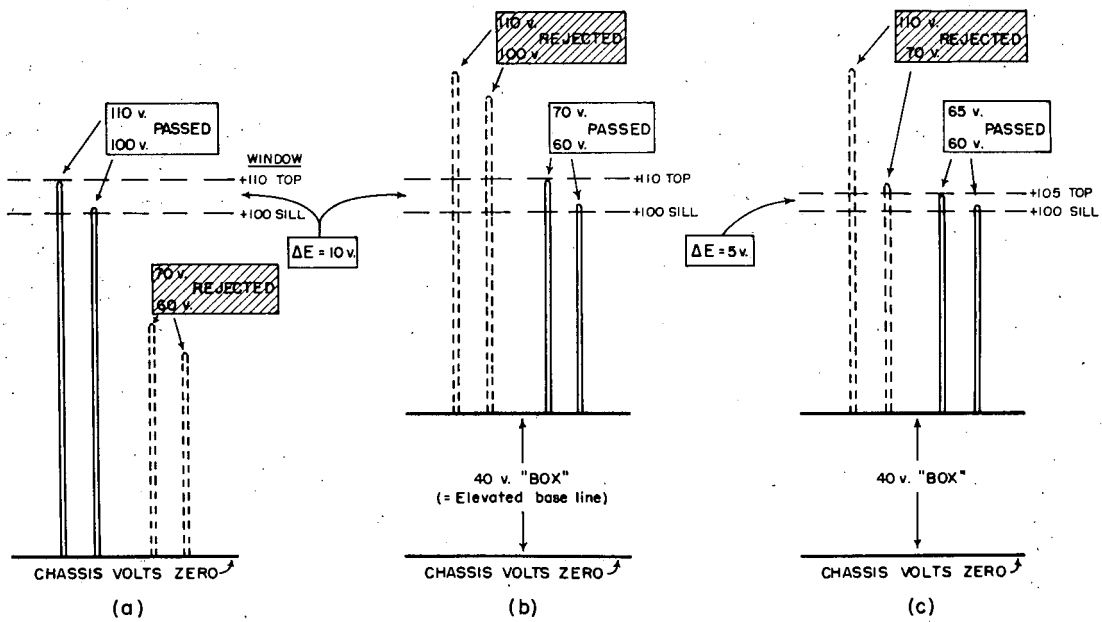

Fig. 14. How "Sill Height" and "Window Opening" Are Kept Independent (See Text).

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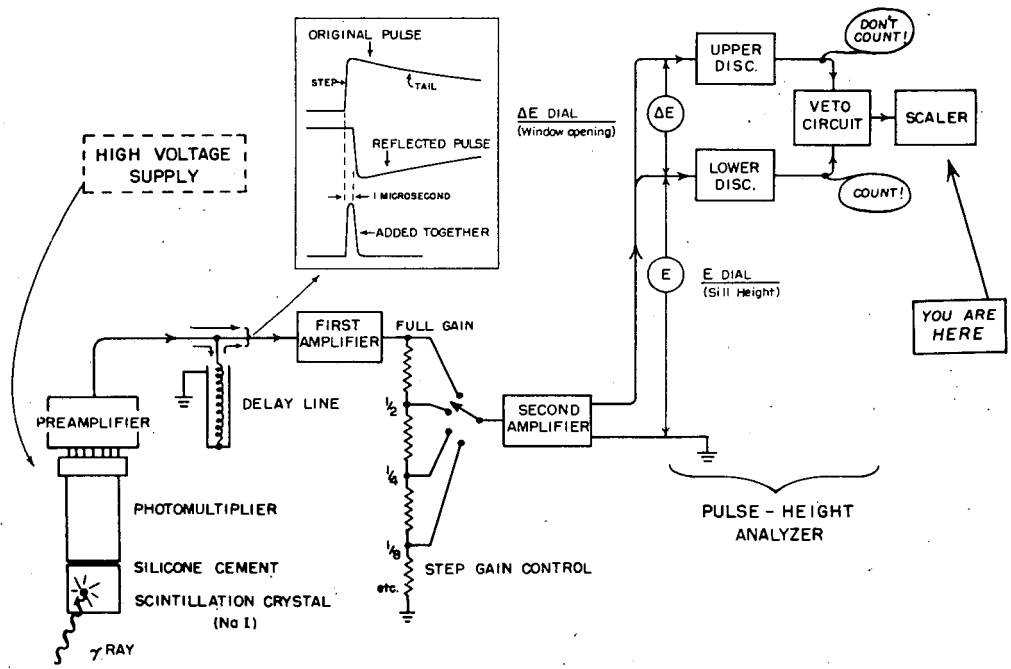

Fig. 15. Completed Block Diagram of the Medical Spectrometer.

Pulse Counting

A pulse-height spectrometer turns out its information in the form of so-many pulses delivered through the window per second or per minute. The Francis-Bell version provides the operator with two different methods for obtaining count rate: (1) the "*integrate*" system, in which the reading of the meter tells the operator the total number of counts, which he then divides by the counting time in order to get counts per second; or (2) the "*rate meter*" system, in which the count per second is indicated directly by the meter hand without further ado. Rate-meter readings are simple and direct, but frequently they suffer from the drawback that the meter's pointer wavers too much for the operator to get a good idea of what its average position is. This will be most troublesome with the low count rates. With the integrate system, on the other hand, the indicating pointer comes to rest when the count is turned off, and the operator can then get a steady reading. This is a great convenience, but it carries the disadvantage that it may suggest a degree of accuracy that is not really there, as readers who are familiar with statistical work will readily realize. In this respect the integrating meter should be no better, and no worse, than a conventional binary or decade scaler, although perhaps one could argue, on purely psychological grounds, that the meter is really better because it provides fewer figures to be misinterpreted.

Integrator. – The reader may recall that at the output of the photomultiplier tube we used a condenser to add up electrons for us, and we can similarly use a condenser to add up pulses and give us the total count over a known counting time. The pulses accepted by the window are fed into a conventional flip-flop scaler, and each time the scaler circuit flips it deposits a small charge, of uniform size, on a kind of glorified condenser. (For those interested in circuits, the device used is the well-known "diode pump.") As the charge accumulates the voltage rises $\left(V = \frac{Q}{C}\right)$, and so the voltage may be inspected by a suitable meter and used as a measure of how many charges have been pumped in – in other words, how many pulses have come through the window. We might compare this arrangement to a chemist's graduated cylinder into which we are allowing drops of water to fall; if we take care to make the drops all the same size, the height of the surface can tell us how many have accumulated, and it won't matter whether they come in rapidly or slowly, regularly or irregularly. Thus when we turn the medical spectrometer's meter switch (under the high-voltage knob) to "INTEGRAL" the meter reading will measure the total number of pulses accumulated during the time when the count was running.

In order to deal with widely varying count rates, the meter is provided with 5 ranges, selected by the switch labeled "METER SCALE" in the lower left-hand portion of the panel. This is the equivalent of having drops of 5 different sizes; with the largest we will be able to obtain visible readings with only a few drops, but with the smallest we can accumulate many drops before the cylinder overflows – or, in the electrical counterpart, before the meter hand is driven off scale. For the reasons explained in the following paragraph, full-scale deflection of the meter hand represents a total count of 100 times the figure at which the METER SCALE arrow is pointing.

In the Francis-Bell spectrometer an internal time is provided, and in normal operation this lets a count run for 100 seconds and then turns it off automatically. The total count can then be divided by 100 in order to obtain the counts per second. Rightly or wrongly, the METER SCALE ranges are so marked that even this division is done automatically, for the figures on the METER SCALE switch tell the operator what a full-scale reading on the meter means in *counts per second*, on the assumption that the counting time has been 100 seconds, which it normally is. This works well enough unless, as sometimes happens, the counting time has to be changed. A count rate can be so high that even on the topmost range the meter will run off scale before 100 seconds are up, or it can be so low that 100 seconds are not enough to provide reasonable statistical reliability. It is easy enough (although a nuisance) to obtain counting times longer or shorter than 100 seconds, for the COUNT switch can be operated manually; to get a long count the timer is disabled by a switch on the rear apron, so that the count will not be prematurely terminated at 100 seconds. The awkward aspect of a nonstandard counting time is the reading of the meter, whose scales are geared to the 100-second period. Personally I think confusion would be avoided if the INTEGRAL system, which measures total counts, were calibrated to read total counts, for I believe I can divide by 100 in my head without serious risk. However, since the instrument has been set up otherwise, perhaps the easiest way out is to read

the short (or long) count in the usual way and then ask yourself what the reading *would have been* had the count been allowed to run for the standard 100 seconds. For example, if the counting time is 25 seconds, and the meter, with deplorable mendacity, reads "800 per second", you would multiply the 800 by 4, since with 100 seconds the meter would, in theory, travel 4 times as far.

We have seen operators estimate high count rates by procuring a stop watch and measuring the time required for the meter's indicating hand to travel from zero to full scale – a procedure undoubtedly suggested by the "preset count" feature in some conventional scaler systems. This stop-watch trick is a very poor idea, because the meter hand does not follow the accumulating counts instantaneously, as a scaler does. While the count is going on, the hand lags behind the actual accumulation, and not until the count stops will the hand catch up and indicate the true total. The amount of lag depends on the rate at which the hand is moving – that is, on the count rate – and thus a variable error is introduced by this procedure. High count rates should be measured on the integral basis by switching the count on, and then off, for a suitably short period of time and using proportion to estimate what the total would have been had it run the full 100 seconds.

An external scaler can be used to count the pulses, and this expedient has considerable merit. Scalers have the advantage of being "open-ended" devices: they can count large or small numbers of pulses equally accurately without the involvement of a range switch, which one might well hesitate to trust. For this and other reasons (e.g. perhaps a more adaptable timing system) a laboratory having an unemployed scaler might care to use it to count the spectrometer's pulses. The demands on the scaler are much less exacting than usual – for instance, nobody would care if its high-voltage circuits were hopelessly beyond repair – so that a decrepit old scaler can be rescued from the junk-heap and be put to good service in this way. If an external scaler is used, however, one must bear in mind that a positive pulse is delivered by the spectrometer when the scaling circuit flips and a negative one when it flops. If the external scaler is so designed that it counts only positive pulses, then it will be counting not every pulse coming through the window but every *other* pulse, and consequently the count indicated by the external scaler will be only half of that derived from the spectrometer's internal counting mechanism.

The RESET button near the spectrometer's meter serves to return the indicating pointer back to its zero position – for example after an integral count has been recorded and the operator wishes to start another. If the zero position is faulty, it can be trimmed by means of the "ZERO" screwdriver adjustment located just to the left of the METER SCALE switch. The meter zero is usually the last thing to settle down when the instrument is turned on from a cold start.

Rate Meter. – Returning to the analogy of the uniform drops of water falling into a graduated cylinder, we can make this device into a rate meter by putting a small leak in the bottom of the cylinder. Suppose the cylinder is empty ("reset to zero") and we start running the drops in at a moderate rate. The surface of the water will rise, but as it does so the pressure at the bottom will increase, and this is the pressure that drives the water out through the leak, so that the rate of leakage increases. Equilibrium will be established when the water is leaking out just as fast as it is dripping in, and when this occurs the height of the surface, which is determining the rate of leakage, can be used as a measure of the drop rate. In similar fashion we can make the condenser in the integrate system, described in the foregoing section, "leak" by connecting a fairly high resistance between its terminals; then the voltage developed across the condenser, which we are already equipped to measure, will be proportional to the count rate.

Such rate meters all have one defect. If you make the condenser large its reading will be reasonably steady but it will take a long time to reach equilibrium, whereas if you make it small the action will be fast but jiggly. Some rate meters offer the user a choice of "time constant" ($= R \times C$, the product of resistance and capacity, which has the physical dimensions of time), so that he will be able to select for himself the best compromise between speed and steadiness, but there is nearly always a squeeze one way or the other. A dodge that can take some of the pain out of a slow-but-steady system (which many spectrometers have) is to use the lower ranges of the meter to accelerate the attainment of the equilibrium position, switching to the proper range only when the hand is nearly at the (guessed) final position; if you overshoot you can turn off the "COUNT" switch briefly. In general, however, rate meters are a curse.

High-Voltage Meter

The high-voltage position of the METER SCALE switch has nothing to do with the counting of pulses; it merely makes the meter indicate the voltage that the regulated supply is delivering to the photomultiplier tube. This switch position is therefore useful as a "standby" for the meter, which cannot then be overloaded accidentally by a high count rate while the operator is setting up a sample or a patient before running a count. It is advisable not to overload the meter because a severe overload causes the zero to shift, and it may take time to settle down again.

OPERATING POLICIES

Introduction

The foregoing discussion of basic principles has stressed the point that the medical spectrometer can count gamma rays *selectively*, according to the adjustment of its controls. In short, it can be made to see what we want it to see. This is an advantage, but it bestows upon the operator the responsibility of setting up the instrument properly, so that it will count the "right" kind of gamma ray and operate with acceptable efficiency. It is all too easy for a careless or uninformed technician to place the spectrometer's window in such a position that much of its value is lost. Here we have a situation in which the interaction between instrument and operator is unusually important: the operator can easily make a monkey out of the instrument, and *vice versa*. Accordingly, we will do well to pause and consider just what it is that we want the window to accomplish for us, so that we can make an intelligent decision as to how high it should be above the ground and how large we should make its opening.

After that we can worry about how to get it placed where we want it.[13]

Pulse-Height Spectra. – The first thing to do is to take a look at the kind of raw material that we will be presenting to the window for analysis. Let us procure a gamma emitter and present its radiations to the detecting crystal. Coming out of the linear amplifier there will be a continual, random barrage of electrical pulses (Fig. 16-a). If the gamma rays striking the detector all carried the same energy, one might expect that the pulses would all be the same size; but this is not so, for the crystal-phototube mechanism is not wholly precise in converting gamma energy to pulse height. There will be a most-frequently-occurring size, (the "mode") in addition to which there will be other pulses, some taller and some shorter. Among the reasons for this dispersion are non-uniformity of the photocathode; escape of some electrons or secondary gamma rays, or both, to

[13] This present handbook concerns itself with basic principles and mechanism. A sequel is planned, in which the actual details of calibration and operation will be described.

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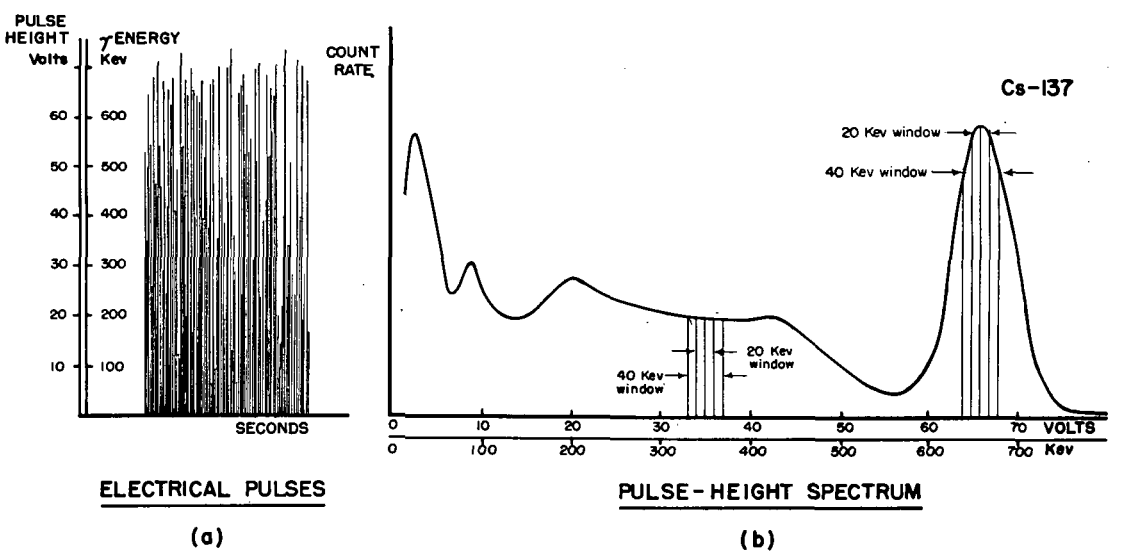

ELECTRICAL PULSES (a)

PULSE-HEIGHT SPECTRUM (b)

Fig. 16. Pulse-Height Spectrum of Cesium-137, in Air.

regions outside the crystal, so that some of the scintillations measure only part of the incoming energy instead of all of it; "dark noise" in the phototube; electronic noise elsewhere in the circuits; and so forth. Accordingly, although pulse height will be proportional to gamma energy, this will be true in a statistical rather than an individual sense, and we must expect a certain amount of looseness in the relationship. Given a quiet and stable amplifier, the dispersion will depend mainly on the crystal and the phototube, and on the skill with which they are assembled and mounted.

We can show the distribution of the pulse heights very nicely by making a "pulse-height spectrum," which is a plot of the various count rates for a whole series of pulse-height categories. Figure 16-b shows the pulse-height spectrum for cesium-137, a radioactive element that ejects an electron to become barium-137. The barium daughter, being in an "excited" state, rapidly settles down to the ground state by emitting gamma rays all having an energy of 662 kev.[14] Following the usual convention, we use the vertical axis in a pulse-height spectrum for count rate and the horizontal one for pulse height. Since the pulse heights are pretty closely proportional to the energies, we can legitimately scale off the horizontal axis also in kev, and for the purposes of this illustration *we have adjusted the over-all amplification so that we get 1 volt of pulse height for each 10 kev of energy.* Accordingly we will expect the 662-kev cesium gammas to produce pulses that are 66.2 volts high. Some of them will be a little taller than this and others shorter, for the reasons explained a moment ago, and so instead of a single "line" at exactly 66.2 volts we obtain a hump with its maximum or "mode" there. This hump we call the "photopeak," and if the isotope in question emits several kinds of gamma rays there will be several photopeaks in the pulse-height spectrum – see, for example, that for iodine-131 (Fig. 17) to which we will be coming in a moment.

The bell-shaped, 662-kev photopeak in Fig. 16 will be understandable enough to the reader, but he is sure to raise his eyebrows at the prominent activity shown by the graph at lower energy levels. On the basis of imperfect resolution one can understand the spread, nearly symmetrical, on either side of the mode at 66.2 volts, but the curve says that there are numerous pulses much smaller than this, and moreover there are several maxima, instead of one, for this allegedly mono-energetic source. It looks as if there is some flagrant monkeybusiness going on, and one has a strong inclination to accuse the spectrometer of gross moral turpitude in its energy-conversion department. Well, the instrument is admittedly guilty of dispersing the line spectrum somewhat,

[14] We often speak loosely of "the 662-kev cesium gamma ray," because we always find it wherever there is cesium-137, but strictly speaking we are referring to the gamma tossed out by the barium-137 daughter. Cesium-137 is important to us because all the released gammas have the same energy; in other words it is a "monoenergetic" or "monochromatic" source.

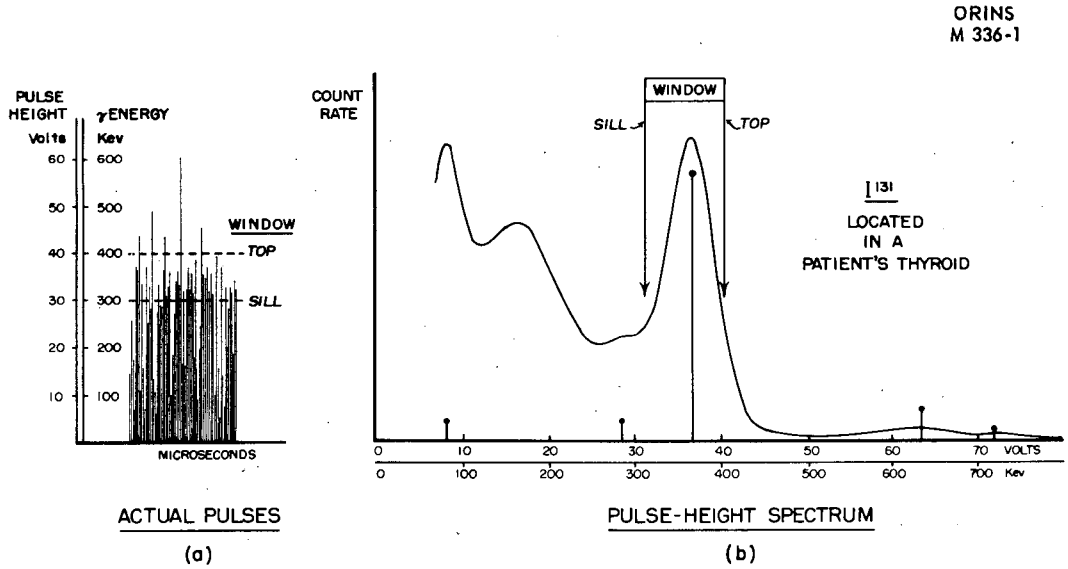

Fig. 17. Pulse-Height Spectrum of Iodine-131 in a Patient's Neck.

but it is not responsible for many of the small pulses seen, for these actually correspond to low-energy gamma photons striking the detector, and the machine is only reporting pretty truthfully what it sees. The chief source of the low-energy distortion is that the radiation changes its character in traveling from the disintegrating atoms to the detector, and it is important to bear this in mind. Many of the 662-kev gamma rays interact with atoms in the source, or in the material surrounding the source (e.g. the patient), or in the air between the source and the detector, or in the materials near the crystal (e.g. the collimator that shapes the crystal's "visual field"), and the usual products of these interactions are free electrons and Compton scatter. Consequently the radiation reaching the crystal is no longer monochromatic; inevitably it contains many low-energy rays that were not originally present, and the spectrometer itself is not responsible for much of the distortion that is found in the pulse-height spectrum. After all, one can hardly blame the instrument for not being able to guess what the radiation was like before it ever reached the crystal.

Degraded radiation, plus some escape from the crystal, will account for the broad, uneven plateau that extends from about 50 to 500 kev in the cesium spectrum, but the lowest peak (32 kev) has an entirely different origin. It is due to the "barium X-ray" that is also emitted from the source. In a body of cesium-137 the barium daughter will always be present, and high-speed electrons tossed out by the disintegrating cesium will strike some of the daughter atoms. This produces X rays just as if the barium were the target in a conventional X-ray tube, and the characteristic energy for the barium K orbit is 32 kev.

It is clear, accordingly, that even with a mono-energetic source there will be a wide variety of pulses presented to a spectrometer's window, and we must bear this in mind when deciding how we should set up the window for a particular counting situation. If the radioisotope in question gives off several kinds of gamma rays, the factors discussed may all be operative, but each in multiple form. By way of example, Fig. 17 shows the pulse-height spectrum for iodine-131, which emits electrons ("beta rays") and several kinds of gamma rays. Along the base line of the spectrum are five vertical lines located so as to show the energies of the five principal gamma rays emitted, and with the height of each line indicating the frequency with which its particular gamma occurs. The most frequent (81 per cent) is at 364 kev, and its photopeak is usually the most prominent feature of an iodine-131 pulse-height spectrum. The 80-kev peak (3 per cent) looks prominent when the iodine is surrounded by scattering material (the patient's neck in this case) because the 8-volt pulses produced by this gamma ray are mixed with many scatter-pulses of about the same size. The analyzing window, of course, has no way of knowing whether an 8-volt pulse is produced by a primary, 80-kev gamma or represents the crippled remains of one of the higher-energy gammas, degraded by Compton scattering. The main scatter-hump in the iodine-131 spectrum has its maximum between 100 and 200 kev, and is derived principally from the 364-kev gamma rays; note that this maximum is not a true photopeak, for it does not correspond with any of the five principal gammas. The humps at 638 (9 per cent) and 720 (3 per cent) are not appreciably augmented by scatter, since there is nothing above them, but they cause scatter that augments, to a hidden degree, the main peak at 364 kev. The infrequent (6 per cent) gamma at 280 kev gives a small photopeak that is almost drowned in the edges of the main peak and its scatter-hump.

It is clear, therefore, that a pulse-height spectrum provides a somewhat distorted picture of the gamma emission of a radioisotope. The distortion does not make the picture worthless, but we must learn to interpret these spectra correctly, and must bear in mind the habits and eccentricities of both the radiation and the analyzer when deciding where to place a window for a particular counting problem.

Incidentally, Fig. 17-b also illustrates how we can conveniently represent the position of an analyzing window on the pulse-height spectrum. The window operates, of course, on a voltage basis, so that what we are calling the window sill represents the lower limit of the voltage range accepted, and its top the upper limit (Fig. 17-a). On a graph showing the actual *pulses*, therefore, the window is best shown as two horizontal lines with a space – the "opening" – between them. When we come to the pulse-height *spectrum*, however, the window is, symbolically, turned over on its side for the low-energy limit is now to the left while the upper one is to the right. One soon gets accustomed to this rearrangement. In operating the instrument, when we turn the "E dial" (= sill height) to the right, so as to move the window up in terms of volts, we move it to the right on the spectrum, toward the higher energies.

When we turn up the ΔE dial to increase the window opening, we increase the span of the window from side to side in the spectrum, for we are making it see a wider band of energies. This is why in many of the commercial instruments the window-opening or ΔE dial is labeled "channel width"; the physicist who specified the label was thinking more of the spectral plot than of the actual opening in terms of volts between window sill and window top. Physicists are like that, and one must try to be tolerant. I think the term "window opening" is much more descriptive.

There are two main questions that we will need to answer in deciding how to set up a pulse-height analyzer: (1) what part of the spectrum should the window be looking at (*window position*); and (2) how wide should its opening be to make it as useful as possible (*window opening* – or, from the standpoint of the spectrum, window "width"). Let us consider the two separately.

Window Position – Principle of Enlightened Rejection. – It is well to remember that the window's basic function is to *reject*; it counts only a smallish fraction of all the available pulses and throws the rest away. Counts should not be thrown away without good reason, for a lowered count rate makes for statistical uncertainty; so we must take care that the window accepts useful gammas and rejects only the unwanted ones, rather than the other way around. In most of the situations where a spectrometer is helpful there will be two kinds of radiation that we don't want to be bothered with: namely, *background* and *scatter*, both of which clutter up the count with misleading or uninformative junk. Sometimes, however, scatter may be entirely tolerable, and other considerations such as stability, or sample-to-background ratio may become dominant. This happens in a well counter, for example, for here the scatter will be the same for the unknown samples as for the known standard, and therefore the desired proportionality between count rate and quantity of radioisotope will not be jeopardized by the presence of scatter. Clearly the best way to use a spectrometer's window will depend on the problem at hand and on what the experimenter wants the window to do for him. Accordingly it will be best to discuss window placement from several points of view, as follows.

Window Position for Adequate Count Rate. – In deciding where to place the window we will be concerned about count rate, because the window will be throwing away counts and we won't want the statistics of the measurements to be compromised any more than necessary. The natural impulse is to place the window over the highest peak in the spectrum, and in most instances this is the sensible thing to do. The large hump provides a better count rate than would be available elsewhere, which helps the operator to achieve statistical reliability without giving an excessive dose of radioisotope to the patient. There is one possible catch: the biggest hump provides many counts, to be sure, but are they all *meaningful* counts? How many of them belong to an honest-to-goodness primary gamma ray and how many are the result of capricious and unmanageable scatter from less frequent gammas higher up in the spectrum? If there is only one gamma, as with cesium-137 (Fig. 16), there is no problem, for there will be only one primary hump and it will be scatter-free; but if there are several gammas, as there often are, each of them will be scattering down into the regions below it, and if the main photopeak lies in such a region, it will be contaminated by the scatter from above. Accordingly, one may have to weigh the advantage of high count rate against the possible drawback of at least some scatter content, and this brings us to the second consideration.

Window Position for Minimum Scatter. – If the material surrounding the emitting source is not under proper control, scatter will be objectionable, for it can't be counted on to contribute the same proportion of counts at all times. In such a situation the variability of the results can be minimized by placing the window in a position where it can't see any of the scatter. From this point of view the preferred photopeak would be the one farthest to the right in the spectrum, for there will be no higher gammas to scatter downward into this hump. But if the topmost photopeak happens to be a small one (cf. iodine-131, Fig. 17) the operator may face a painful choice: which hurts more, a low count rate with substantially no scatter content, or a higher count rate that includes some scatter? The answer will depend on how serious the problem of scatter is, and on whether one can ease the pain of a low count rate by utilizing expedients that compensate for it – for example an increased counting time. If you are counting a patient, there will be a limit to the time during which he can fairly be expected to lie still, whereas if the count is from a surgical specimen or a cadaver you need consider only your own convenience. Each counting situation will require individual evaluation.

With iodine-131, which illustrates this kind of problem, there is usually no serious trouble. A patient's thyroid can be counted with the window straddling the 364-kev photopeak (Fig. 17), and contamination with scatter from the two higher gammas is not enough to be bothersome. The higher-energy rays are few in number in the first place, and moreover they are highly penetrating, so that they usually produce only minor amounts of degradation within the space visible to the detecting crystal. Ordinarily, then, the operator simply accepts the contaminating scatter with good grace, since it does not disturb the over-all picture at all seriously. If it should become troublesome, he can move his window up and count the upper photopeak, which will be substantially scatter-free. This expedient will, of course, saddle him with a reduced count rate and a more troublesome collimation problem.

Another way of reducing the importance of scatter is to count the main photopeak with a narrow window, for this, as explained later (see section on window opening and background, S/N ratio, etc.), will increase the ratio of main-peak pulses to scatter pulses. This alternative will also involve a reduced counting rate, although background and scatter are reduced proportionately more than the desired signal is. The best compromise will depend on the particular problem.

Window Position for Good Stability. – When we place a spectrometer's window over a photopeak, we *adjust it to the point where the count rate is maximum,* not only because we want the best statistics we can get, but also because we want the system to be stable. In spite of all the regulating circuitry, changes in line voltage and other things may make the window shift its position slightly up or down, but if it has been placed right at the peak it can move a little without changing the count very much, because for a short stretch on either side of the on-center position the rate is nearly the same. This matter of stability will be considered in greater detail in the section dealing with the choice of window opening.

Window Position for Low Background. – A normal laboratory background is due to minute quantities of radium, potassium, and other radioactive elements in the building materials, with a contribution from cosmic rays and the scatter produced by them. If lead shielding is used, it also contributes a small component, since some of the isotopes of lead, present in minute amounts, are radioactive. In a typical background the lower energies predominate, so that its pulse-height spectrum is highest at the left-hand end and falls off as one goes to the right, becoming very low in the higher-energy ranges (Fig. 18). This is the situation in a well-run laboratory, but if there is a neglected spill somewhere, or an inadequately shielded storage vault not far away, the background spectrum may well show humps suggestive of the spilled or poorly shielded isotope. In any case, the lower energies are likely to predominate, which means that a background count tends to be lower if the window is high. However, the position of the window is likely to be a less important consideration than its opening, and we will be coming back to this a little later.

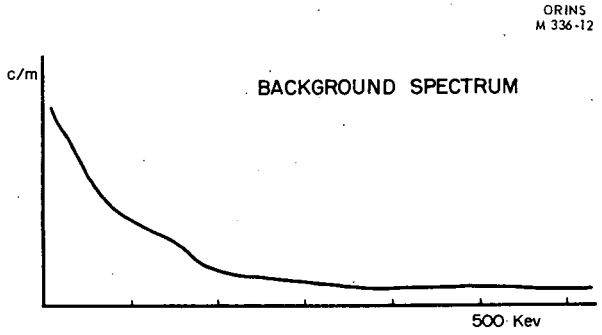

Fig. 18. Spectrum of a Normal Laboratory Background.

If an elevated background is unavoidable, try to arrange things so that it is *steady,* for then it will be much less pestilential. It is the variable backgrounds – due to X-ray equipment nearby, "hot" patients wandering around in neighboring rooms, and so forth – that drive an operator out of his mind.

Window Position for Multiple Isotope Studies. – The ability of the medical spectrometer to pick out an individual photopeak for counting, and disregard the rest of the spectrum, gives the operator the privilege of counting two isotopes separately, even if they are present together in the same sample. The only stipulation is that the two spectra must be reasonably dissimilar, for one can't disentangle two photopeaks if they overlap seriously. Ideally one would like to find two window positions, one for each isotope, so located that there would be no cross-contamination, but this is too much to expect. The *higher* of the two chosen photopeaks is often substantially uncontaminated by the lower, but inevitably the upper gamma will scatter downward into any window placed below it, so that the isotope seen

by the lower window will always be polluted with counts derived from the other one.

Let us take chromium-51 and iron-59 as a typical example, for it is often desirable to use these two together as diagnostic tracers in a blood study. The two spectra are shown in Fig. 19. The chromium is "monochromatic," with a single gamma ray at 320 kev; the iron has two high-energy gammas at about 1100 and 1300 kev, and the spectrum shows a massive plateau[15] between these and a third gamma at 191 kev. It is clear that if we use a window with its sill at 1000 kev we will be able to count the iron without interference from the chromium, but a chromium-centered window will see numerous pulses generated by the upper iron gammas. Such pulses will, of course, have nothing to do with the chromium count, and they will obscure it just as room background does. The iron contaminant in the lower window will, however, be proportional to the amount of iron present; there will be a certain percentage of the net upper-window count that will be thrown into the lower window. We can determine this percentage, once the positions and openings for the two windows have been frozen, by counting a pure iron-59 sample with the upper and then with the lower window, taking care to deduct the appropriate room background in each case (they will not be the same) before the percentage is calculated. In a practical situation the lower-window contamination might be 15 per cent of the net upper-window count, although this figure will depend on the window positions and openings and on the geometry of the crystal assembly. Having established this percentage, we can turn to an unknown, mixed sample and count it with the upper window; comparison of the net count with that obtained from a known iron-59 standard tells us at once how much iron is there, since the upper window is well beyond the chromium range. This count also tells us, however, that 15 per cent (let us say) of these counts will be present, in addition to room background, when we count the sample for chromium. Accordingly we count with the chromium window and deduct (a) the previously measured room background, and (b) the calculated iron contamination. The remainder is the net chromium count, and it tells us how much chromium is present through comparison with a known, iron-free, chromium standard.

If the two isotopes are chromium-51 and iodine-131, as they might well be, the only reasonable way to get an estimate of the iodine present is to count the two topmost iodine gammas (638 and

[15] This plateau is due not so much to scatter as to partial interactions in the crystal. The upper two iron gammas are hot, and their secondary gammas will also be highly penetrating; thus they "escape" relatively easily. As explained earlier (see "Limitations Inherent in Scintillation Spectrometry"), partial interactions give substandard pulses.

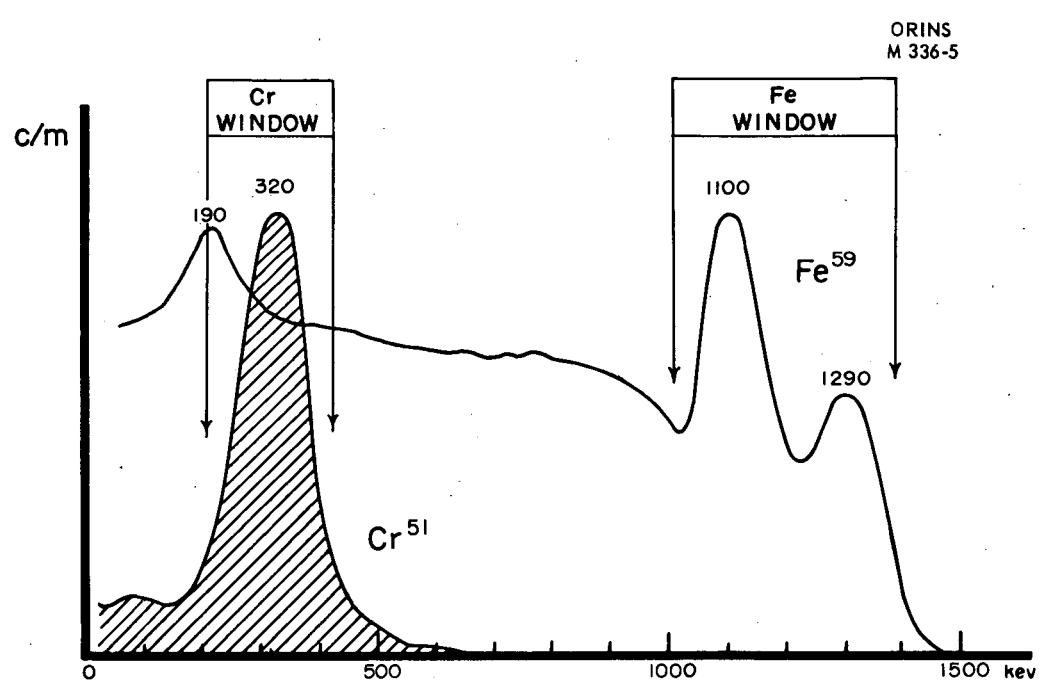

Fig. 19. Plan of Attack for an Iron-Chromium Mixture.

720 kev), since the main iodine photopeak will always be heavily contaminated by the 320-kev chromium gamma. Here we have an exception to the usual rule that iodine-131 should be counted with a window centered on its main photopeak. For further details on the counting of an iodine-chromium mixture consult Francis, Bell, and Harris: Nucleonics, 13, No. 11, page 88, Nov. 1955.

Window Opening

After deciding where to locate the window over the pulse-height spectrum, we must ask how wide its opening should be. Here also, as in the foregoing section, we have several things to consider, and should take them up one at a time. Before we start, however, there is a principle to be established; it is important because it helps to clarify the relationship between count rate and window opening.

Count Rate and "Enclosed Area". – This principle is that the count rate will depend on the *AREA* that the window can "see" under the curve of the pulse-height spectrum – that is, the area enclosed between the two vertical lines representing the top and bottom of the window. To understand the reason for this, let us return to Fig. 16, the pulse-height spectrum for cesium-137. These spectra are obtained by placing a narrow window successively at a whole series of elevations and measuring the count rate for each position, which gives us, in effect, the count per minute for each narrow band of gamma energy. We label the vertical axis of the spectrum "count rate," but what we really mean is "count rate per kev of window opening," for if we widen the window we will naturally see more gamma rays and thus raise the count rate. Without getting too deeply involved with the concepts of the integral calculus, let us suppose that the spectrum was constructed by taking counts with a 1-kev window, placed successively at the various energy levels covered by the horizontal scale. If we want to find the count rate for a window that is spanning the range 600 to 601 kev, we imagine a narrow, vertical strip standing with its lower end on the base line between 600 and 601 and reaching up until it hits the curve. The height of the strip is, of course, an index of the count rate, which can be read off against the vertical scale at the left.

Suppose that for the 600 to 601 kev strip the reading is 2000 c/m, while for 601 to 602 kev it is 2100. If we plant a 2-kev window so that it spans from 600 to 602, clearly it will see all the pulses passed by the two 1-kev windows, and therefore its rate will be 2000 + 2100 = 4100 c/m. Expanding the argument, for a 20-kev window we would be adding up 20 vertical strips instead of two, and consideration of the figure will show that what we have done, in adding up these strips, is to find the *area* lying under the curve, enclosed between the upper and lower limits of the window at 600 and 620 kev.

The conclusion is that no matter where a window is located on the pulse-height spectrum, or how large or small we make its opening, the count rate delivered will be proportional to the area "seen" by the window.

Window Opening and Count Rate. – In terms of this area concept we can readily understand what will happen if we center a window over a photopeak and then begin to increase its opening, keeping its center at the original position. As the opening increases, strips of area will be added on at the sides, so that the count rate will go up. But there is a law of diminishing return here: as the edges creep downward on the sloping sides of the hump, the newly added strips become shorter and shorter, so that finally, when the edges are riding low on the curve, there is little to be gained by opening the window further. It is clear that count rate will *increase with* window opening, but will not be *proportional to* it; if we double the opening we are not likely to double the count.

There are exceptions to this rule, and the most important of these arises when the window is looking at a flat part of the spectrum. Going back to cesium-137, Fig. 16, let us place a 40-kev window with its center at 350 kev. The figure makes it clear that this window will see just about twice as much area as will a 20-kev window at the same location, because here the spectrum is level and the two outside strips are very nearly as tall as the two inside ones. In the region of the 662-kev photopeak, however, a 40-kev window will see *less than twice* the 20-kev area, because the outside strips are shorter than the middle two. Flatness in the spectrum makes for the proportional relationship, whereas a hump destroys it, causing the count rate to increase more slowly, percentagewise, than the window opening. This distinction is important particularly in connection with background, because in most places the *background* spectrum is more or less flat, and therefore background will be approximately proportional to window opening. This brings us to the next topic.

Window Opening and Background; "S/N Ratio" and Statistical Accuracy. – In the pulse-height spectrum of a typical background, peaks and troughs are notably absent; the spectrum starts high, relatively, at the low-energy end and falls off progressively as the energy increases (Fig. 18). Consequently there is little curvature throughout any stretch of 100 or so kev that a run-of-the-mill window is likely to see, and background will be nearly proportional to window opening, for the reasons discussed in the preceding section. This raises a potential problem, for it follows that if we keep a narrow window centered on a photopeak and begin to widen its opening so as to get more counts, the background will increase faster than the sample counts. In engineering language, the "signal-to-noise ratio" (S/N ratio)[16] deteriorates as the window is widened, and this represents a retreat from the usually desirable situation where the signal is, as the engineers say, "sticking its head well up out of the mud," so that it can be seen and measured.

[16] To the electronic engineer, the "signal" is whatever he wants to see, hear, or measure – that is, the important or significant component in the electrical output of his amplifier or other device. "Noise" is the unwanted trash that is inevitably present as a contaminant (e.g. tube microphonics, A.C. hum, burps, squawks, static, etc.), and he tries to keep the noise down to a level that is not bothersome. In our case most of the "noise" is the radioactive background – that is, radioactivity not related to the source we are counting – for the electrical hash can nearly all be excluded by means of suitably adjusted threshold circuits.

Figure 20 shows in concrete terms how a narrowed window opening can give a substantial boost to the S/N ratio. The upper curve shows the spectrum for a weak sample of cesium-137, the count rates being recorded in a situation where the background was intentionally made high by removing the usual shielding around the crystal and planting, a few feet away, a lead pot containing a 5-millicurie radium standard. After this combined spectrum had been recorded, the cesium sample was taken away and a repeat run was made to obtain the spectrum of the background alone, shown as the lower of the two curves. Area measurements, in arbitrary units, are given in the adjoining table.

The figures remind us that the improvement in S/N ratio is obtained only at the cost of reduced count rates, and so a narrowing window will sooner or later reach a point at which the lowered rates begin to hurt more than the low S/N ratio. Here we are faced with two basically conflicting trends; how are we to steer the best middle course between them?

Well, one way to deal with this kind of trouble is to keep out of it, by planning doses in such a way that the things we are going to count will contain reasonable amounts of radioactivity. This will keep the "signal" part of the S/N ratio from sinking down too close to the "noise." We can also keep the background low by good shielding, good laboratory housekeeping, and other appropriate measures. Every so often, however, even our best efforts will leave us with a weak signal

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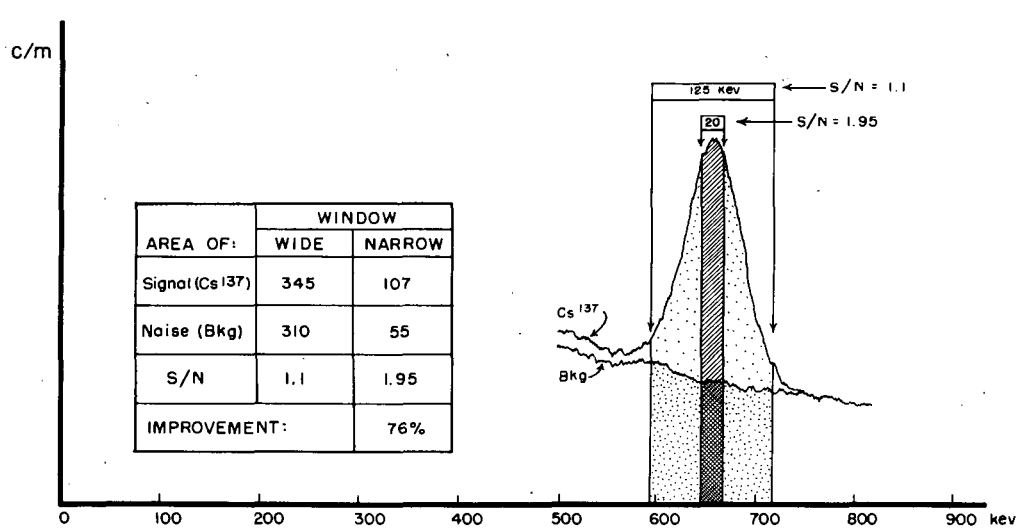

AREA OF:	WINDOW WIDE	WINDOW NARROW
Signal (Cs 137)	345	107
Noise (Bkg)	310	55
S/N	1.1	1.95
IMPROVEMENT:		76%

Fig. 20. Effect of Window Opening on Signal-to-Noise Ratio.

that the background threatens to drown out, and we must establish some practical policy for choosing a window opening that will be as helpful as possible.

Various people have tried to devise simple rules that can serve as guides, and interested readers are referred to articles by Loevinger and Berman,[17] Freedman and Anderson,[18] and others in their lists of references. A frequently cited rule of thumb is that one should try to make the ratio $\frac{(\text{net counts})^2}{\text{background}}$ as large as possible. This rule is based on a number of assumptions, plus an approximation. One assumption is that the sample and background counting errors are due entirely to random variation in the counts, with no added sources of error due to either the instrument or the operator. In such a case it is legitimate to estimate a standard deviation by taking the square root of the number of counts, and on this basis the expected coefficient of variation, or "per cent standard deviation," will be given by $\frac{100\sqrt{S + 2B}}{S}$, where "S" is the *net* sample count (*not* the count rate) and "B" is the background, counted for the same length of time. This gives us an estimate of the error we must expect to incur whenever we subtract a background from a gross count. If we concentrate our attention on those harrowing situations where the net sample count is considerably smaller than twice the background, we can use $100\sqrt{2B/S}$ as an approximate estimate of the *error* – or, which amounts to the same thing, we can use $S/\sqrt{2B}$ as an indication of the *accuracy*. We will want this quantity to be a maximum, which means that its square must also be a maximum; hence the rule that $(\text{net sample})^2/\text{background}$ should be as large as possible. For purposes of comparison it doesn't matter whether we use the background or twice background, and for the same reason we can leave out the factor 100.

Figure 21 shows how the expected error varies as the window is widened, the per cent standard deviation being plotted for four different S/N ratios, as indicated at the left. The error curves are the sickle-shaped ones in solid lines, and they are derived from the formula $\frac{100\sqrt{S + 2B}}{S}$.[19] They are plotted on a logarithmic scale, which means, in effect, that their shapes indicate the per cent changes in error, rather than the actual changes; on a linear scale the lower curves would be so flat that we would have difficulty drawing conclusions from them. In relating the sample and background rates to the window opening, the assumption is made that the photopeak has the shape of the "normal curve of error," and this is drawn in, with linear co-ordinates, so that one can see at a glance where the edge of a given window would cut the side of the photopeak. A representative window is shown, with a total opening of 2 standard deviations. Near the top of the "bell," the rather flat curve – and this curve would be much less flat if plotted on linear co-ordinates – shows how the S/N ratio falls off as the window is widened; the S/N ratios are plotted as per cents of the maximum or narrow-window values because this ratio depends on the sample as well as the window. For the 2-SD window shown, the S/N ratio will be about 85 per cent of the maximum value.

Let us procure a sample in which the net count rate is twice background when both are measured with a narrow window, and see what will happen when we look at this sample with the 2-SD window. The S/N curve says that the net count will fall to 1.7 times background; the error curve, for S/N = 2, says that we should expect a standard deviation of 5 per cent if we were to count this sample many times. This means that about two thirds of the measurements (gross minus background) would lie within ±5 per cent of the average, while the other third would be off by more than 5 per cent.

Note that if we narrow this window further we will not improve the S/N ratio much, for it has already reached 85 per cent of its best attainable level with this sample. The statistics, on the other hand, will get worse, and rapidly worse at that, because of the falling count rates.

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[17] Loevinger, R., and Berman, M., Efficiency Criteria in Radioactive Counting. Nucleonics 9, No. 1, 26–39, July 1951.

[18] Freedman, A. J., and Anderson, E. C., Low-level Counting Techniques. Nucleonics 10, No. 8, 57–59, 1952.

[19] In calculating the points for these curves, background was arbitrarily taken as 100 counts for a half-window of 0.2 of an S.D. With this opening, then, the net count would be 50 for S/N = 0.5, 200 for S/N = 2, and so forth. Perhaps it would have been more realistic to base the family of curves on a background of 1000 counts, but all this would do would be to divide all the errors by 3.16 ($\approx \sqrt{1000/100}$), without changing their interrelationships in any way.

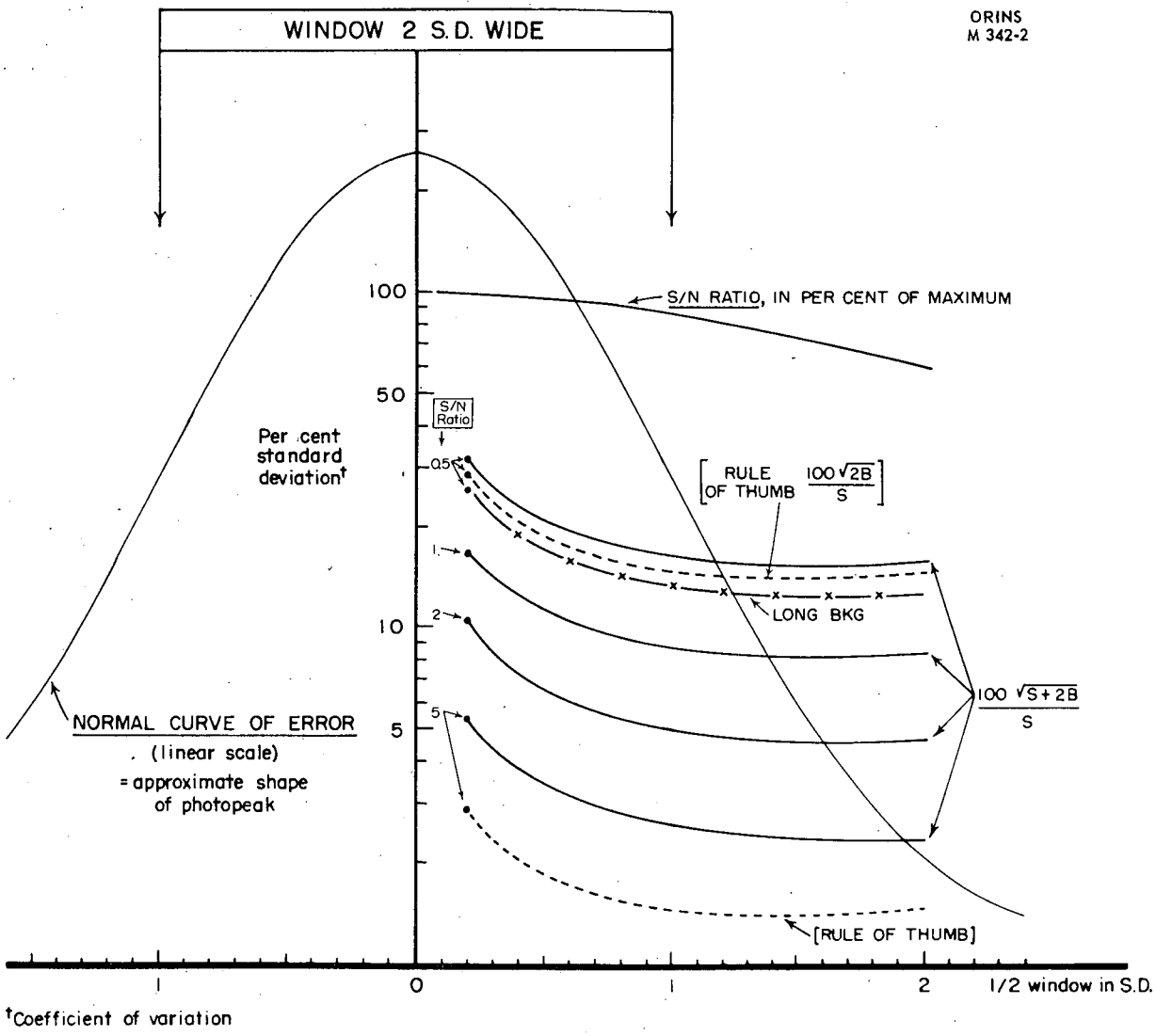

Fig. 21. Reduction of Statistical Uncertainty as Window Opening Is Increased.

The error curves bring out the important point that *the errors get smaller as the window is widened, in spite of the deteriorating S/N ratio.* To put it another way, the operator who seeks accuracy through a narrow window, arguing that he must improve his S/N ratio, is barking up the wrong tree; it is more important for him to get higher count rates. Certainly let him strive toward a better S/N ratio *by other means* – increasing the dose, improving the shielding, and so on – but not by narrowing the window.

This is good news, because, as we shall see in the next section, considerations of stability urge us to use a wide window if we can, and the only cloud on the horizon is the reduced S/N ratio. We know now that this is no problem at all, since the wide window more than pays for its poor S/N ratio through improved statistics.

The accuracy doesn't continue to improve indefinitely, of course, for the curves level off; in fact, some of them go through a minimum and then begin to climb very slowly as the window is widened further. This doesn't happen, however, until the window can see most of the photopeak.

The broken curves are added in to show what sort of advice the "sample^2/bkg" rule of thumb would have given us. To avoid complicating the picture unnecessarily, only the curves for S/N ratios of 0.5 and 5 are put in. Since the rule of thumb is beamed at the situation where the signal is almost disappearing into the mud, we are not surprised to observe that its curve lies close to

"true" curve at S/N = 0.5 but is much farther away when the ratio is 5. With good S/N ratios, therefore, the rule of thumb becomes misleading, and makes the system look much better than it really is. Nevertheless, it does show pretty well where the curve begins to climb, and thus it can be used to warn us when we should not make the window any smaller.

One additional curve is thrown in for good measure; it is the one marked with crosses. As mentioned earlier, the $\frac{100\sqrt{S + 2B}}{S}$ formula is derived on the assumption that the counting times for the unknown and the background are the same. The reader will not have to be told that the background, which has the lowest count rate of all, could be established more reliably if a longer counting time were used, and this should improve the statistics. The background count has the enormous advantage that nobody has to lie still while it is being run, and so a long background count may be inconvenient but is by no means unobtainable. The curve marked with the crosses[20] shows the improvement to be expected if background were counted five times as long as the sample, which would increase the background's reliability by a factor of $\sqrt{5} = 2.24$. Regrettably, the gain is not great, although every little helps if one is scraping the bottom of the barrel for signal counts. The improvement is still smaller for higher S/N ratios, for then the background is less important, and its accuracy is less critical.

The foregoing analysis is based on the assumption that a photopeak has the shape of the "normal curve of error" – the familiar, bell-shaped curve that the mathematicians refer to as "Gaussian." Actually the upper half of the photopeak of a monoenergetic gamma emitter approximates the Gaussian curve quite closely. The lower half is complicated by the intrusion of the scatter plateau (Fig. 16), and it is fair to ask whether this will seriously modify the conclusions we have drawn from the theoretical analysis. We think not. We might worry if the photopeak in the practical situation were *sharper* than the Gaussian, because this would mean that the S/N considerations would be more important; but actually the peak is made *less* sharp by the scatter, which makes us more inclined, rather than less so, to prefer a wide window as far as signal-to-background problems are concerned. The not-strictly-Gaussian shape of an actual photopeak strengthens, rather than weakens, the case for the wide window.

Window Opening and Count-Rate Stability. – If a technician is told to center a window over a prominent photopeak, he can fairly ask how carefully this must be done. He can argue that if the window is placed slightly to one side of its correct position the rate will still be almost maximum, so there will be little loss of efficiency if the setting is not precisely "on center." But we must also consider what will happen if the hump should drift to one side (e.g. due to a change in amplification), or if the hump stays still but the window moves a little up or down. No ordinary electronic instrument is capable of retaining a setting indefinitely with mathematical precision, and the operator should expect that at least some drifting will occur. This is especially true of devices using photomultiplier tubes, for in these the over-all gain, which determines the pulse height and therefore governs which energies a given window will see, is critically dependent on the high voltage supplied to the phototube. It is true that the medical spectrometer's designers have made strenuous efforts to stabilize the high voltage, but no regulating circuit can be perfect and the line voltage may fluctuate beyond all reason.[21] Moreover, the photomultiplier gain is temperature-sensitive, whether or not the high voltage can be held constant within half a gnat's eyebrow. So when we speak of a photopeak's shifting its position spontaneously we are considering a very real possibility, and we must try to minimize the hazard by setting up the window in such a way that the count will not change *much* if the window drifts or if the gain changes a little. Count rate will be dependent on window position, of course, but we would like it not to be critically dependent.

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[20] Coefficient of variation

$$= \frac{100\sqrt{S + B \cdot \frac{t_s}{t_b}\left(1 + \frac{t_s}{t_b}\right)}}{S}$$

where t_s and t_b are the counting times for sample and background. Note that this reduces to the other formula when $t_s = t_b$.

[21] This is particularly prone to happen in hospitals, where the ritual of polishing linoleum floors seems to be ineradicably carved into the administrators' code of honor. It would be a tremendous boon to nuclear medicine if all floor buffers were unconditionally banished, for their ceaseless, erratic loading and unloading of the power lines is an unmitigated curse to any laboratory that needs a steady line voltage.

The area concept is helpful in clarifying what goes on when a window drifts. If we keep the center of a window in a fixed position, and merely increase the opening, strips of area will be added on at the sides, and the count rate will always rise. When the window's position is shifted, on the other hand, without change in opening, area is gained at one side but lost at the other, so the effect on count rate will depend on whether the gain outweighs the loss, or *vice versa*. Figure 22 shows a drifting window; initially it straddles the main photopeak symmetrically, but as time goes on it drifts upwards, toward the higher energies, as shown by the pulse diagram at the left. On the spectrum itself, the vertical strip of area at the left-hand edge of the window represents lost counts, while that at the right represents counts gained, and since the window opening remained constant these two strips will have the same width. They will not have the same height, however, for the strip at the left is tall whereas that at the right is shorter.

Our concern is with the difference between these two strip areas, for this is a measure of change in count rate. We can simplify things by drawing in a few horizontal lines, which will let us cancel out equal components that are found at both edges. Thus we note that there is a "loss rectangle" at the left that will be counterbalanced by the corresponding "gain rectangle" at the right; similarly there is a "loss triangle" at the left that will be approximately equal to the "gain triangle" at the right, although to make them exactly equivalent the slopes would have to be the same on both sides of the hump. There remains a rectangular area at the left that has no counterpart on the right, and since it represents the unbalance between the gain and loss areas we can label this rectangle "net loss." The larger it is, the greater will be the change in count rate, and so to achieve good stability we must keep it small for a given window displacement. That is, given the width of the rectangle we want to minimize its height. The diagram makes it clear that to do this we should keep away from the steeply sloping limbs of the hump, and locate the edges of the window either high up near the top or down near the bottom, where the curve loses its steepness. Accordingly the problem boils down to a choice between two kinds of window: a wide one covering most of the photopeak, or a narrow one placed right at the top. We know already that the former will give a better count rate; which is preferable from the standpoint of stability? If drifting must occur, how much will the count rate change?

Well, we have asked the wrong question, for we aren't so much interested in the *actual* change in count rate as we are in the *per cent* change. We need to consider not only the size of the net-loss rectangle, but we must ask what fraction (percentage) of the original area seen by the window the net loss represents. Going back to the spectrum, we can see that if the window is made very narrow the whole of its width will lie within the nearly flat portion of the spectrum at the top of the hump, so that if it moves *a little* the net-loss rectangle is bound to be small. With a narrow window, however, the original enclosed area will also be small, so that even a small

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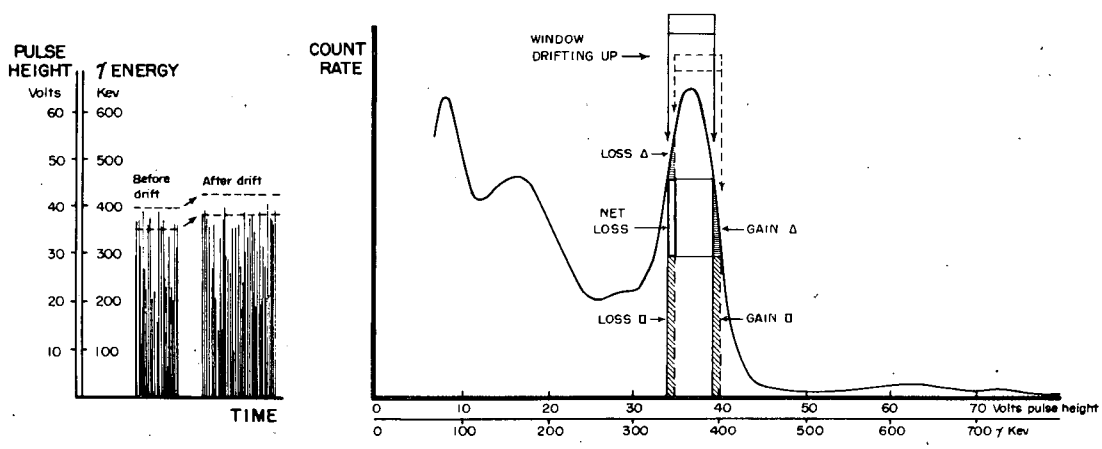

Fig. 22. Unstable Window Drifting Upward.

actual change may constitute an appreciable per cent change. We conclude that a narrow window, carefully centered at the top of a photopeak, will tolerate *small* displacements well but will be vulnerable to any that carry either of its edges beyond the "flat" region at the top of the hump. Once this happens, rate changes will set in rapidly, and will cause marked percentage errors.

In other words, the narrow-window system has a narrow margin of safety, and anyone who is forced into using it should use all means at his disposal to minimize drifting. Suitable precautions might well include a restricted instrument line, from which no intermittent, heavy-duty equipment can be operated, an auxiliary regulating transformer[22], and so forth. The operator should also try to keep the temperature of the room in which the instrument is operated as constant as possible – particularly the temperature in the neighborhood of the detector. (If you decide to air-condition the instrument room, do *NOT* operate the conditioner from the instrument line!) Last but not least, he must be careful to center his window right at the top of the chosen photopeak, and even then the margin of safety will be narrow.

A window riding on the sloping side of a photopeak is, of course, asking for trouble, for it will be highly vulnerable to drift. In fact, a sensitive test for stability in a pulse-height analyzer is to plant a narrow window on one side of a photopeak and follow the count rate for a time to see how stable it remains, since any drifting tendency in either the window position or the gain will show up in the count rate at once. But it is hard to imagine anybody's being rash enough to use the side of a photopeak for the running of routine counts. When we run a pulse-height spectrum, of course, we take counts all over the hump, sides included, but apart from these special situations the steep sides are good places to keep away from.

Now contrast the narrow-window situation with one in which the window is wide enough to straddle the photopeak, so that its sill and top cut the curve down near the bottom where the slope is no longer steep. Maximum count rate will occur when the edges intersect the two limbs of the curve at the same height above the base line[23], and this is the way the window should be set up. As a consequence of the moderate slope the net-loss rectangle will be reasonably small; moreover, the total area seen by the window is large, so that a given area change caused by drift is likely to be a small percentage of the total. Accordingly the wide window not only gives a better count rate, it also provides a greater degree of inherent stability. The original placement of the window is not very critical, and if the position does drift, within reason, the per cent change in count rate is likely to be negligible.

In the foregoing discussion we have made no distinction between a drifting window and a drifting gain; in the former case, illustrated in Figure 22, the window moves with respect to the photopeak, whereas in the latter the photopeak creeps out from under a stationary window. Actually these two kinds of drift are not strictly comparable, though in perhaps the majority of practical situations there is no important difference between them. If a drifting photopeak moved to one side or the other without changing its size, we could fairly apply the same argument that we used for the drifting window, but the trouble is that a peak *does* change its size as it moves. If it shifts to the right it becomes shorter and fatter; to the left it gets taller and thinner.

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[22] With the MS-1-A medical spectrometer, one might as well come right out and say that a line-voltage-regulating transformer is a necessity, for almost no power line will be so stable that the transformer will not be needed. These transformers should be properly chosen and properly used. Their output voltage is substantially independent of the input (= line) voltage over quite a fair range, but the output will change if the *load* is altered, so the transformer should drive equipment in which none of the components gets turned on and off. Moreover, the demand should be suited to the transformer, loading it well up near its rated capacity. For the 105-watt MS-1-A, for example, a 120 v-a regulator should be used, since the 250-v-a size costs more, burns up more power, and does not do as good a regulating job with a 105-watt load.

Keep the detector at least 4 feet away from the regulating transformer, for the latter sprays the surrounding countryside with a magnetic field that alternates at 60 cycles per second, and this can disturb the electron pathways in the phototube, changing the electron gain. This hazard can also be reduced by providing *proper magnetic shielding* (Mumetal or equivalent) *around the phototube*, which is a good plan anyway because the transformer is not the only source of trouble. It is common practice nowadays, for example, to magnetize screwdrivers and other tools, and meters and recorders often contain powerful magnets. Even the earth's magnetic field, weak though it is, can affect the electron gain of an unprotected photomultiplier.

[23] To convince yourself of this, look at Fig. 22 again and consider the initial position of the window. Whether it drifts up or down, the strip of area representing loss will always be taller than that representing gains, so that either way the count will fall. This can only mean that the highest rate will occur when the points of intersection are the same distance above the base line.

This complicates the analysis, though it does not make it impossible.

Figure 23 shows how the pulse-height spectrum for chromium-51 changes when the gain is increased by one-third over the usual value; the 320-kev peak, normally at 32 volts, moves out to about 43 volts, and its height is reduced at the same time. Looking at the curves, one might suspect that the total area lying under a spectrum doesn't change much as the gain is altered, and a little consideration will convince us that it shouldn't change at all. Whether the spectrum is spread out or squashed together, the whole area under it represents the total number of pulses per minute, irrespective of pulse size; the total number of pulses is the total number of scintillations, which depends only on the incoming radiation, and not on how the gain is adjusted. Accordingly when the gain changes, the total area does not, and if the area is to remain constant, all the peaks in a spread-out spectrum must necessarily be lower than those of a normal one. In fact, we can predict quantitatively how much lower they will be. If, as illustrated in Fig. 23, the gain increases by one third (that is, is multiplied by 4/3), the constant-area rule requires that each point on the curve must reduce its height above the base line in the ratio of 3/4, and this is why the primary peak in the shifted spectrum is only 3/4 as high as in the normal one.

On the basis of the inverse proportionality between gain and peak height, one can explore the gain-change problem mathematically. We recall that when a window shifts with respect to a stationary photopeak, the position for maximum count rate, and therefore for maximum stability also, occurs where the sill and top of the window cut the photopeak at the same height above the base line. It turns out that in order to provide protection against drifting gain, the count rate where the sill cuts the curve should be *higher* than the count rate at the window top, the ratio between the two rates being the same as the ratio of window-top voltage to sill voltage. When the window is either high or narrow this ratio will be near unity, in which case an adjustment designed to protect against gain change will also be good for window drift. If, on the other hand, a window opening is wide enough to represent a sizable percentage of the sill height[24], so that

[24]This is the rule rather than the exception in beta scintillation counting.

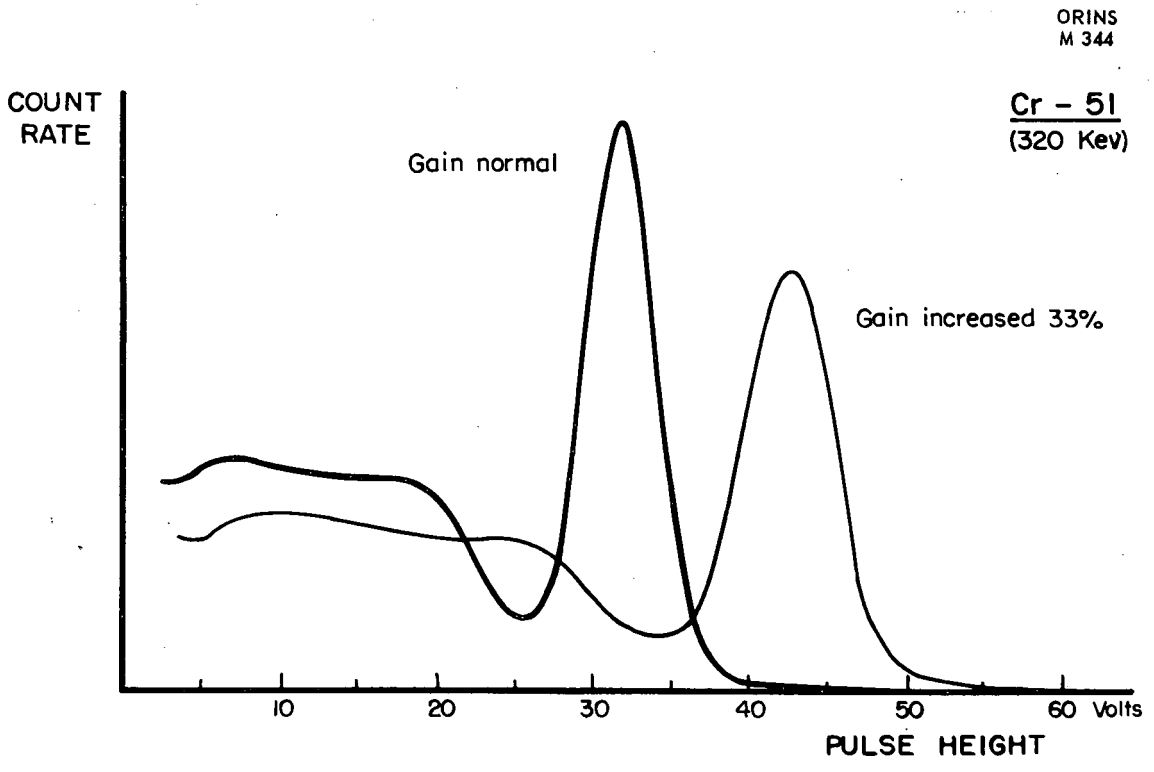

Fig. 23. Effect of Increased Over-All Amplification on the Pulse-Height Spectrum of Chromium-51.

one adjustment will not cover both contingencies, an operator will usually do best to protect himself against gain change, since a drifting gain is more likely to occur than a drifting window. In such a case the position of maximum count rate should be found by adjusting the high voltage, rather than by searching it out with the E dial.

Plotting a Pulse-Height Spectrum. – A pulse-height spectrometer can be used to plot a spectrum, of course, and occasionally this is desirable and even necessary. For example, if the operator is planning to count a mixture of two isotopes, he needs to know what the spectra are *in the actual counting situation* (complete with scatter, dispersion, etc.) before he can make an enlightened decision as to where he should place the two windows and how wide each should be. Again, he may come to doubt the purity of a radioisotope he is receiving, and want to run its spectrum to see whether it contains any humps that shouldn't be there; or again, he may suddenly discover contamination in his laboratory – or, still worse, personnel – and need to know at once what the contaminating isotope is. In such situations a spectrum is often helpful and may be of vital importance.

It goes almost without saying that for the plotting of a spectrum a narrow window is essential, for a large window sees a wide band of gamma energies and the finer details of the spectrum become lost – or "smeared" to borrow a rather unlovely term from the engineers. The narrow window brings with it the drawbacks of poor counting rates and reduced stability, and long counting times invite trouble from drifting. It is a good plan, therefore, to start with a sample having somewhat higher activity than usual, and of course all reasonable precautions should be taken regarding constant room temperature, generous warm-up time, and well stabilized AC power. Moreover, if an appreciable background is present it must be determined and subtracted out for each window setting; this is such a terrible chore that time devoted to getting the background down to a negligible level is likely to be well spent.

A word of caution should be added regarding the use of a medical spectrometer's window at low settings. For reasons having to do with necessary design compromises, the reliability of the window is likely to vanish when the sill is brought down near the base line. Consequently there is a rough-and-ready rule that the E dial is not to be trusted at settings below 70 divisions or so, although some instruments do better than others in this regard.

Scatter Rejection. – With a pulse-height spectrometer it is usually easy to avoid the counting of scatter-pulses, for when the window is set up on a prominent photopeak nearly all the scatter falls below the sill and is therefore ignored. Sometimes, however, the main photopeak carries concealed within it scatter-pulses derived from less frequent gamma rays of higher energy. This happens to a minor extent in iodine-131, for example, in which the photopeak at 364 kev is routinely contaminated with small amounts of scatter derived from the gamma rays at 638 and 720 kev. In the case of iodine-131 we normally ignore this problem, because the scatter-pulses from the upper two gammas contribute an inconsequential percentage to the main photopeak[25], but with other isotopes this might not be so. If trouble is anticipated from this source, there are ways of coping with it. One can construct an artificial "phantom," whose absorption and scattering characteristics closely imitate those of the part of the body containing the radioisotope, in which case both the main-photopeak pulses and the scatter-pulses will be proportional to the amount of isotope present, and little risk will be incurred if scatter is included in the counts. Or one can abandon the main photopeak and count only the highest-energy gammas, in which case the scatter will fall below the window. This last expedient will involve a reduced count rate, of course, and any advantage will have to be evaluated against this drawback.

What about the optimum window opening; should we use a wide window here, too? Not quite so fast, for this situation is a little different from the ordinary background problem. Then we were *subtracting out* something; here we are *neglecting* it,[26] which we have to do because we have no reasonable way of measuring it. If something is going to be ignored, it should be only a minor percentage of the total count, so here there is more urgent need for a good S/N ratio, and therefore for a somewhat narrower window. Let us not overdo it, however; we remember that when the

[25] By contrast, the scatter produced by the 364-kev gammas is far from negligible. It makes a prominent hump in the iodine-131 spectrum, lying for the most part between 100 and 200 kev (Fig. 17) and if the measuring instrument can see these energies the errors involved may be considerable.

[26] More precisely, we are neglecting *changes* in the scatter; if it is present in constant percentage we need not worry about it.

edge of the window is about two thirds of the way up the side of the photopeak the S/N ratio will not improve much more (Fig. 21), and there is little to be gained by narrowing further. Little to be gained and perhaps much to be lost, in terms of poor counting statistics.

Multiple-Isotope Counting. – We have touched on this subject before, in connection with window position, but nothing was said then about window opening. What about wide versus narrow windows here; should we shoot for high count rates or for a good S/N ratio? The earlier discussion argued that the high count rates are more important, and what we need to do now is to inquire whether the assumptions on which the argument was based are still reasonable when applied to the double-isotope situation. We must again assume, since we have no better choice, that the square root of the number of counts will predict, approximately, the standard deviation. We can also assume that the photopeaks will be Gaussian, for this will be no less true with two isotopes than with one, and, as mentioned before, departures from the Gaussian shape will be in the direction that strengthens the conclusion rather than weakens it. Can we also assume that the background spectrum, which is now a composite affair, will still be essentially flat, so that background will be proportional to window opening?

Perhaps we will make things easier if we simply ask whether there is anything in the double-isotope situation that could make the background increase *faster* than the window opening, since if it either varies as the opening, or increases less rapidly, we will not need to change the wide-window policy. The only time when count rate increases faster than the window opening is when the window is looking at a trough in the spectrum, for then the edges of the widening window climb up the sides of the trough, and area is added on faster than when the spectrum is flat. Room background is not likely to have any such troughs in it, but conceivably the "contamination background" might. In order to upset our policy, however, such a trough would have to come just where the lower photopeak lies, and this is highly unlikely. Usually the lower photopeak will fall at a place where the plateau produced by the "upper" isotope is either flat, which is favorable to the earlier conclusion, or actually humped, in which case the situation is even more favorable. Here again, it seems, the increased count rates are more important, and the S/N ratio takes a back seat. Apart from rare exceptions, we should use a window that sees most of the photopeak in each case, and leave it at that. As before, we use *other* expedients to boost the S/N ratio, but not a narrow window. The most important "other" expedient is to plan the doses of the two isotopes in such a way that the one with the lower-energy photopeak will be well above the combined background in the mixtures. In the case of iron and chromium, we would try to keep the Cr/Fe ratio high, judiciously steering a middle course between a chromium dose so high that the patient's health is threatened, and an iron dose so low that its counts wallow spinelessly in the background mud. A bit of second sight is very helpful.

In a chromium-iron study there are usually several samples collected on the first day, and after that they come in one or two a day for two or three weeks. Not all studies will be similar to this, of course, but whether the samples become available slowly or rapidly, it is a good plan to count a fair number of them at each sitting, so that the instrument does not have to be set up and calibrated on many different occasions for the same set of data. The recommended policy minimizes the opportunity for human *error in* setting up the analyzer and adjusting its high voltage, gain control, E and ΔE dials, and so forth. Ideally one should set up only once and run all the samples together, but there will be times when the operator, for one reason or another, will need to know what the early samples look like before the later ones become available. The early samples can always be saved and recounted when all the others are in, although this involves some duplication of effort.

IT IS MOST IMPORTANT that two standard samples should be on hand for every counting run, whether there are few or many. One of the standards should contain pure iron-59 and the other pure chromium-51, and each should be a known percentage of the administered dose, whether the actual microcuries are accurately known or not. When such standards are available, the samples in each run are evaluated in terms of the standard, (and therefore in terms of the dose), which is desirable because if minor errors are made in the setting up of the instrument, the standard and the samples will suffer to about the same degree and the ratios will still be nearly correct. Moreover, if the operator counts the standards before running through the unknowns, he can compare these counts with those of earlier runs, correcting for decay, and any suspicious discrepancy will warn him that something is (or was) wrong with the

instrument or its settings. It is risky to set up the instrument the first time and determine "counts per minute per microcurie" for each window, with the guileless confidence that whenever the dials are again set to these same readings the spectrometer will repeat its original performance. Theoretically this should be so, but it is much safer to rate the unknowns in terms of common standards, carefully retained until the whole series is finished. This approach, incidentally, sidesteps decay corrections, although this is a relatively unimportant advantage.

To tie the foregoing discussion together, the essential steps in the procedure can be summarized somewhat as follows:

(1) Set up the detecting crystal, shield, and so forth, that you plan to use for the actual counts.

(2) See that the analyzer is provided with an adequately stabilized source of power; turn it on and let it warm up overnight.

(3) Obtain a pure sample of iron-59, contained in a test tube or other container as for the counting of the unknowns. Using a narrow window, run its pulse-height spectrum. The count rates should not be excessive, but should be well above background.

(4) Similarly run a spectrum for a sample of chromium-51, plotting it on the same graph as that for the iron (*cf.* Fig. 19). Check to see that the "plateau" from the iron is reasonably flat in the region of the chromium photopeak; there is no cause for concern unless it is strongly concave.

(5) On the basis of the iron spectrum, select a position and opening for the "upper window." You might as well shoot for both of the high-energy iron gammas; there are tricks that will enable you to get a wide window opening with a high-energy sill (see section on "Large Window Openings"). Put the chosen window in position, trim its adjustment for maximum count rate, and count the iron sample and the upper-window room background. These should be long counts, so that the contamination can later be established reliably.

(6) Choose the "lower window," taking care to use an opening that brackets most of the chromium photopeak. This will provide good stability, and will also favor statistical differentiation between target and background (Fig. 21). Using the chromium standard, trim the adjustment for maximum rate, and then count the *iron-59* standard and the lower-window background, using long counts. From the *net* counts of the iron with the two windows, express the lower-window count as a percentage of the upper-window count. This is the "contamination percentage."

(7) With the lower window, count the chromium dose standard, all the mixed unknowns, and the chromium standard again.

(8) With the upper window, count the iron dose standard, all the unknowns, and the standard again.

Armed with these data, and fortified with good checks between the recounts of the standards and the two determinations of the contamination percentage, the operator can then calculate the iron and chromium contents in the unknowns, as percentages of the dose. Background for any iron count is simply the upper-window room background. Background for a chromium count is the lower-window room background, which is presumably constant, plus the calculated iron-dependent contamination for the sample in question.

The foregoing deals with a typical situation where the two photopeaks used for counting are well separated, so that the upper window is essentially uncontaminated by the lower isotope and the only problem is how to cope with the contamination of the lower window. But what if the two photopeaks are close enough together so that the upper window is also in trouble, not because of scatter but because the tail on the high side of the lower hump contributes appreciably to the upper window counts? Or because infrequent, high-energy gammas from the lower isotope can be seen by the upper window (e.g. I^{131} and Cs^{137})? In such a case the analysis is more complicated, but it is still perfectly possible.

To get the symbols defined, let us call the two isotopes "upper" and "lower" according to the positions of their photopeaks on the energy scale. We will need a lower and an upper window, each designed to see one of the photopeaks, but each isotope will throw a certain fraction of its own counts into the other fellow's window, just as the iron did to the chromium. When we present an unknown sample, therefore, each window will see a mixture; let us call the rate M_1 for the lower and M_2 for the upper, M standing for "mixed." These are to be the *NET* count rates, after subtraction of the proper room background in each instance. Our assignment is to derive P_1 and P_2 (P for "pure"), the net rate that each window would see if only its own isotope were present and the other were not there. Once we have P_1 and P_2 we can convert each into a percentage of its own dose by comparing it with the count for the pure standard that we have taken care to save.

The lower isotope will throw P_1 c/m into its own window and a fraction kP_1 into the upper one, and we can determine this "k" by using a pure sample of the isotope, as we did with the iron-59. Similarly the upper isotope throws P_2 c/m into the upper window and $k'P_2$ into the lower. Accordingly we have two equations:

$$M_1 = P_1 + k'P_2 \ , \quad \text{and} \quad M_2 = P_2 + kP_1$$

and there are only two unknowns, since M_1, M_2, k, and k′ can all be measured. A high-school student can tell us the solutions:

$$P_1 = \frac{M_1 - k'M_2}{1 - k'k} \ , \quad \text{and} \quad P_2 = \frac{M_2 - kM_1}{1 - k'k} \ .$$

What the high-school student will probably *not* do, however, is to view these pretty solutions with the jaundiced eye of a more seasoned experimenter, who has learned, the hard way, of the perfidy that may lurk behind an innocuous-looking subtraction sign. The numerators, each being a difference, will be on very shaky ground if the terms being subtracted are anywhere nearly equal, for in this event the small difference can incur a whopping error.[27] Putting it another way, one can't expect even modest accuracy if the counts seen by a window consist mainly of contamination from the wrong isotope; it's the old stumbling-block of a weak signal sinking down into the background mud. Mercifully, the upper isotope may contaminate the lower window fairly heavily (*cf.* Fe 59 and Cr 51), but unless the photopeaks are quite close together the lower isotope probably will not contaminate the upper window *much*, so that k will be small and the estimate of P_2 reliable even if fairly large quantities of the lower isotope are present (which helps to make *its* estimate reliable). However, if there is considerable overlap between the humps one should search for some other plan of attack. In the case of iodine-131 and chromium-51, for instance, the 320-kev chromium hump tangles so horribly with the 364-kev iodine hump, that here the experimenter will be well advised to swallow his pride and count the iodine, uncontaminated, by means of its upper two gammas at 638 and 720 kev, making up for the reduced count rates by taking longer counts. This approach is much less wishful than the simultaneous-equation method, which, in this instance, would demand impossible accuracy in the measurements.

[27] For example: 105 ± 1% − 100 ± 1% = 5 ± 28% (the percentages are the coefficients of variation, or "per cent standard deviations").

Energies Above 1000 kev (= 1 Mev)
Unusual Gain Adjustments

In the foregoing discussions of pulse-height spectra we have assumed that a 662-kev cesium gamma ray would give a pulse 66.2 volts high; or, in general, that the ratio kev/volts = 10:1. Clearly this ratio would change if we altered the amplifier's voltage gain or the phototube's electron multiplication, since with more over-all gain the same gamma photons would produce taller pulses (*cf.* Figure 23), but the 10:1 ratio simplifies the discussion. It so happens, however, that this gain adjustment is usually the best one to use in actual practice as well. The E dial is a 10-turn potentiometer with 1000 divisions on its scale, while electrically it has a range of 100 volts. If we use the 10:1 ratio the 100 volts will represent 1000 kev, and thus each E-dial division comes to be equivalent to 1 kev – an obviously convenient arrangement.

Once in a while, however, we will be pinched because the E dial will not have a large enough range. With the 10:1 adjustment, the highest window sill will be at 1000 kev, and the highest top at 1100 kev, since the maximum window opening is 10 volts. Several medically important isotopes have gamma rays with energies beyond the reach of a 1000 to 1100 kev window – for example sodium-24, potassium-40, iron-59, cobalt-60 and others. What are we to do about these?

Well, clearly we must either increase the voltage range of the window or reduce the size of the pulses, and it is much easier to do the latter. Lowering the high voltage fed to the photomultiplier will cut down the electron multiplication, or we can reduce the gain of the amplifier by means of the step gain control. In the latter case the gain is halved each time the knob is turned one notch to the left. In the Francis-Bell spectrometer full amplification is called "32" on the dial, and on this basis the other figures, "16", "8", "4", and "2" are self-explanatory. The resistors in the dividing network are allowed a tolerance of ±5 per cent, since there is no point in trying to make the ratios exactly 1:2.

One way or another, the experimenter who wants to count iron-59 can so reduce the gain that pulses from the 1100-kev iron gamma fall into a window whose center is at 550 dial divisions;

thus each division represents 2 kev instead of the usual 1. With such an adjustment, the cesium-137 gammas will be seen by a window centered at 331 divisions, chromium-51 at 160 divisions, and so forth. The operator selects the relation between gamma kev and dial divisions largely on the basis of his own convenience; if he dislikes mental arithmetic (as many of us do) he uses the one-E-division-per-kev relationship wherever it is suitable, and if he needs some other he at least keeps the ratio in nice, round numbers. For iron-59 he might prefer to make 1 division = 4 kev.

The E dial may be set up in the following way:

(1) Present the detector with a source (preferably monochromatic) delivering gamma rays of known energy;

(2) Place a narrow window (say 20 divisions) so that its *center* lies at a dial reading corresponding to the gamma energy in question; if the source is chromium-51, for example (320 kev), put the E dial at 310, since the center of a 20-division window will be 10 divisions above the sill.[28]

(3) Adjust the high voltage so that the *primary* photopeak (i.e. the topmost one) is brought in under the window, an event signalled by the count rate's passing through a maximum. The E dial will then read 1 kev per division.

Large Window Openings

The ΔE knob controls the spacing, in volts, between the top of the window and the sill, and when the knob is turned full right the opening is 10 volts. Since the ΔE dial has 100 divisions, each division should represent one-tenth of a volt, just as it does with the E dial (where 1000 divisions represent 100 volts), and accordingly one ΔE division always corresponds to one E division, whatever the gain adjustment may be. For electronic reasons this correspondence is not too precise, but let us assume it for purposes of discussion.

One result of the equality between E and ΔE divisions is that when we calibrate one we calibrate both: if the operator has made one E division represent 1 kev, then each ΔE division also represents approximately 1 kev. This is a useful thing to bear in mind because sometimes an operator needs a window opening of more than 100 kev, and he can increase the effective window span by reducing the gain.

We can see how this need might arise by returning to the spectrum for iron-59 (Fig. 19). We will usually want to count this isotope with a window accepting both of the upper gammas (1100 and 1290 kev), which would require an opening extending from about 1000 to 1400 kev. We can achieve such a span if we make each E-dial division, and therefore each ΔE-dial division, represent 4 kev, which we can do by presenting a cesium-137 sample to the detector and adjusting the over-all gain so that the primary cesium photopeak (662 kev) lies under a window centered at 165 dial divisions. Then if we turn the E dial up to 250 and open the window (ΔE) to maximum, the window sill will lie at about 1000 kev and the top at 1400, so that it will cover most of the upper two iron-59 photopeaks. For good stability the high voltage can then be cautiously trimmed to give maximum count rate.

Cautious adjustment of the high voltage is recommended because the phototube gain changes *very rapidly* with high voltage,[29] and if the control is handled carelessly an operator may run right through a primary photopeak without knowing it, and set the window up on one of the scatter-humps, in which case the standardization will be a long way from where it is supposed to be. This happens to most of us occasionally, and when the error is discovered there is weeping and gnashing of teeth, for few mistakes can make an operator feel more abysmally stupid.

"Per Cent Window Opening". – The foregoing section emphasizes the fact that the ΔE dial's *divisions* do not always represent *kev*, for the relationship depends on how the gain is set up, just as in the case of the E dial. But the count rate depends on how many *kev* are bracketed by the window, and so if we want a spectrometer to deliver consistent count rates on successive occasions we must take care that the window is set up the same way each time. The change in count rate with an unchanged ΔE setting can be shown strikingly as follows. Using a cesium-137 source, set up the E dial to give 1 kev per division as described a moment ago. A 20-division window will then tune in the primary cesium photopeak with the window sill at 652 divisions,

[28] Such a window may conveniently be described as "320 ± 10." We will see in a moment that the E and ΔE divisions are equivalent.

[29] In the Francis-Bell circuit it is not difficult to add a fine adjustment for the high voltage, and this can spare the operator considerable wear and tear.

because this brings the middle of the window to 662 divisions, corresponding to the cesium gamma ray at 662 kev. Now turn the GAIN knob one notch to the left; this will reduce all the pulses to about half their former size, and in order to pick up the photopeak again the window will have to be moved down until its center is at approximately 331 divisions. When you tune in the peak at this lower level you will find that the maximum count rate has gone up, the reason being that the window now covers more kev than before. Originally the 20-division opening represented 20 kev, but at half gain, with the center of the window at 331, the divisions on both dials represent 2 kev, so that the 20-division window now has a span of 40 kev. The doubled span is what makes the count rate increase; usually the rate will not actually double, but it will certainly go up.

Sometimes it helps to think about window opening in terms of the *percentage* of the middle-of-the-window reading. In the example cited, the window started out with its center at 662 and a 20-division span; accordingly this is a "662 ± 10" window, or 662 ± 1.5 per cent. At half gain, however, it becomes 331 ± 10, which is 331 ± 3 per cent; the effective opening is doubled, and the window spans twice as many kev as before.

There is a practical lesson in the foregoing considerations. A technician will sometimes find, on returning to her instrument after being away for an hour or so, that the photopeak she is interested in has moved 10 or 20 divisions, and rather than readjust the high voltage, which is a nuisance, she might decide to make a new count after simply readjusting the E dial to the new peak location, which is much easier. It is important to realize that if this is done the sensitivity changes because the per cent window opening changes; in fact, it changes by about the same percentage as the drift in the position of the photopeak, the relationship being inverse, so that when one goes up the other goes down. For example, if a chromium photopeak, originally at 320 divisions, drifts down to 300 divisions – a 6.3 per cent change – the window, if its dial setting is left alone, increases its *kev span* by about 6½ per cent. Whether the *count rate* increases by the same per cent is another matter; this depends on whether the part of the spectrum seen by the window is flat or humped (see Fig. 16). If the technician makes the new measurement by comparing with a standard, which is good policy anyway since it avoids several kinds of misery, the odds are that she will come out with the right answer, but she should know that *the new window is not the same as the old unless it peaks at the same E-dial setting*. And if she is inclined to argue that the difference is negligible (as it might be), the burden of proof rests on her.

CONCLUSION

This handbook is intended to help an isotope-oriented doctor or technician understand what a pulse-height spectrometer is all about, what it can do for him that will be helpful, and what he should not expect it to do. Let us briefly summarize the medical spectrometer's virtues and vices. It offers the operator:

(1) A means of finding out, *easily*, what energies the instrument is counting, and the privilege of changing them to suit the individual problem;

(2) Relative freedom from errors brought about by uncontrolled scattered radiation;

(3) A greatly improved signal-to-background ratio, since most of the background is out of sight;

(4) Improved stability, if the instrument is set up properly;

(5) Greater freedom in using more than one isotope, for the instrument can, within limits, pick out the characteristic radiations individually;

(6) A powerful tool that can be used to check the purity of a radioisotope, or establish the identity of an unknown one, through the plotting out of the gamma-ray spectrum.

On the other hand, the medical spectrometer makes these advantages available only at a price. It is somewhat more expensive than an ordinary "threshold" scaler, which has, in effect, a window sill but no window top. There are more tubes and other components in the spectrometer to get out of order. It requires more informed and careful operation, with frequent checking of the adjustments, for it is a booby trap for the ignorant or careless operator. Finally, it presents a terrible temptation to visitors and other prowlers who love to twist knobs just for the fun of it.

ORNL-2808

Contract No. W-7405-eng-26

BASIC PRINCIPLES OF SCINTILLATION COUNTING

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DATE ISSUED

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION

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BASIC PRINCIPLES OF SCINTILLATION COUNTING FOR MEDICAL INVESTIGATORS

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INTRODUCTION

The purpose of these notes is to assist the reader in gaining an understanding of the basic principles of scintillation counting. We will consider the things that happen in a scintillation crystal, the difficulty often created by the crystal and source surroundings in getting precise measurements, and the operation of some counter systems. It is felt that for this discussion we need not go very deeply into electronics. It is further felt that a firm understanding of the happenings in the scintillation crystal and the surroundings is necessary for the proper use of a particular instrument in the light of its capabilities and shortcomings.

In the following material it is assumed that the reader possesses at least a rudimentary knowledge of the major particles of matter. The reader will need an elementary understanding of the structure of atoms and to know what radioactivity nuclei, positrons, and electrons are. An excellent reference for this material is the following: W. H. Beierwaltes, P. C. Johnson, and A. J. Solari, *Clinical Use of Radioisotopes*, p 25–42, W. B. Saunders Co., Philadelphia, 1957.

A gamma-ray emitting radioisotope introduced into a patient can be detected because the gamma rays can get out of the body, since the body itself is a poor absorber for gamma radiation. Higher activity in any body region can likewise be spotted, because more gamma rays will be given off from this area than from the surrounding areas.

Radioactive tracer methods can provide the physician with a valuable diagnostic tool. However, when a radioactive substance is placed in a biological system such as a patient, the physical complexities add to the biological problem. The investigator must understand the physics of the situation to avoid being misled. The following material will assist the reader in understanding gamma-ray emission in the body and how detection measurements can be obtained with maximum accuracy and reliability.

INTERACTION OF GAMMA RAYS WITH MATTER

The analyst will be using some type of detector to measure the gamma rays issuing from the body and in order for him to make correct interpretations, it is necessary to understand the reactions that take place within this detector. Also, knowledge is needed to interpret the character of radiation escaping the patient. Gamma rays interact individually with all matter in essentially three ways:

1. *Photoelectric absorption* occurs when a gamma ray enters some material and gives all its energy to an electron of an atom in the material. The electron then becomes a *photoelectron*. A reaction of this type predominates when a gamma ray incident on sodium iodide has an energy below about 200 kev (kev is an abbreviation for kilo-electron-volt, which is the unit of energy applied to x rays; for example, a 200-kv x-ray machine produces x rays of energies up to 200 kev).

2. *Compton scattering* is the principal mode of interaction for gamma-ray energies from about 300 kev to 5 Mev in sodium iodide (5 million-electron-volts = 5000 kev). In this case the gamma ray strikes an electron of an atom and shares part of its energy, and both recoil from the atom. An analogous situation occurs when two billiard balls collide, for here we know that the resulting energy of each ball depends on its direction of scatter.

3. *Pair production* occurs when a gamma ray reacts with the nucleus of an atom and disappears after having created an electron-positron pair (the *positron* is another particle, similar in mass to the electron but possessing a positive charge, whereas the electron has a negative charge). Nature does not tolerate a positron in a field of many electrons for long, and the positron reacts with an electron to form two gamma rays. (Since the positron and electron disappear, this is called *annihilation*.) These secondary gamma rays leave in opposite directions, each having an energy of 511 kev. This reaction cannot occur unless the energy of the incident gamma ray is above 1.02 Mev but is unimportant below about 2 Mev.

The energy ranges quoted for the first two processes are characteristic of sodium iodide only. Some ranges for other materials are:

1. In tissue and water, Compton scattering almost completely dominates except below 20 kev.

2. In lead, photoelectric absorption is important up to 1 Mev, and pair production rises steeply for

increasing energy above 1.022 Mev. Relatively few Compton interactions take place.

This basic information on how a gamma ray reacts with matter can aid the analyst in predicting how this radiation will be modified after leaving a source within the patient's body. The major differences are due to the size and shape of the material that the gamma penetrates, but any knowledge concerning their interaction will help in interpreting the results obtained with a scintillation counter.

SCINTILLATION COUNTING

Fundamental

Certain materials have the property of giving off a flash of light, or *scintillating*, when struck by ionizing radiation such as gamma rays. The gamma ray itself does not directly cause the luminescence, but instead sets into motion electrons; these cause the flash of light. When a light-sensing device is attached to this special material, a flash of light can be transformed into small electrical impulses. These bits of electrical information may be sorted and counted to determine the amount and nature of the radiation striking the scintillating material. This is the basis of scintillation counting.

There are many materials which scintillate when struck by ionizing radiation, but sodium iodide (activated with a trace of the element thallium) is, for most purposes, the best material for counting gamma rays. Optically connected to the sodium iodide crystal is a light-measuring device called a photomultiplier (see Fig. 1). Inside the cylindrical glass envelope of the photomultiplier is an amber-colored surface, the *photocathode*, and then a series of metal plates or *dynodes*. The flash of light in the crystal resulting from the incoming gamma ray causes electrons from the material of the photocathode to be ejected. These electrons are drawn to the first dynode, where they strike hard enough to knock out more electrons. An average of two to four electrons are emitted when one electron strikes a dynode; so by using a series of ten or more dynodes, we end up with a shower of perhaps a half million electrons at the collector (called an *anode*). This constitutes very large amplification of a current that originated from a very feeble flash of light.

The current *pulses* (and the voltage pulses that result) that the photomultiplier gives are usually very small, but an additional electronic amplifier makes these pulses larger so that they can drive a *counter*, or *scaler* (see Fig. 2). Another piece of information may be gained from these pulses: their final amplitude or *height* can be proportional to the incident gamma-ray energy. Higher-energy gamma rays give larger flashes of light, and this in turn knocks out more electrons from the photocathode for amplification. In effect, we can

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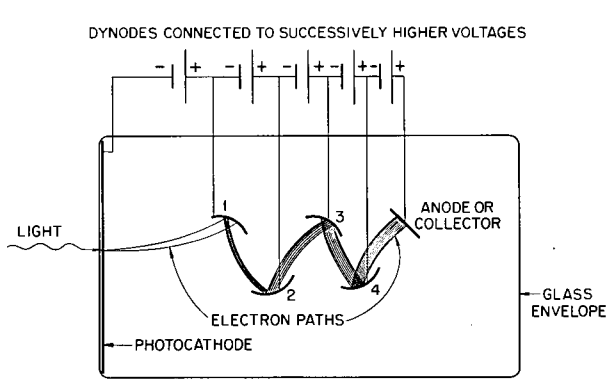

Fig. 1. Simplified Representation of a Photomultiplier.

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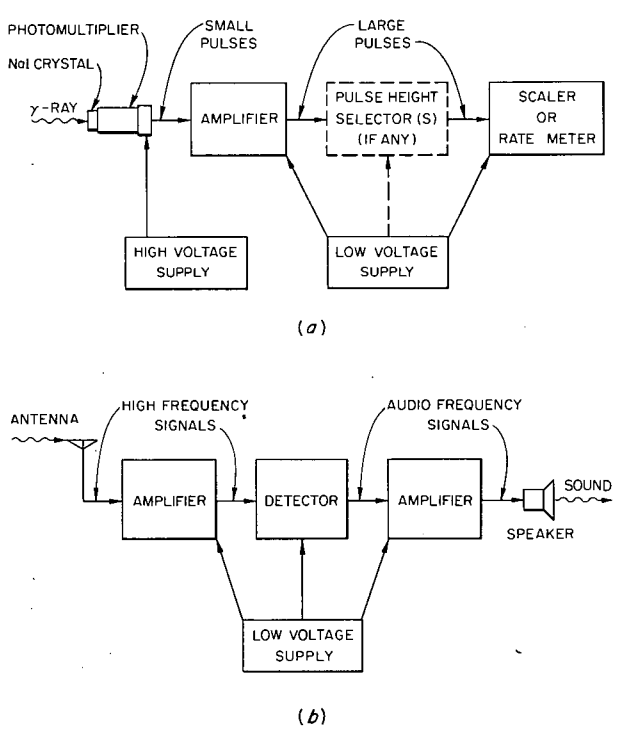


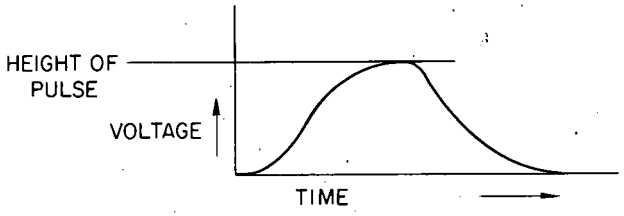
Fig. 2. (*a*) Counting System for Scintillation Counting, Comparable in Simplicity to the Diagram (*b*) for Simple Radios.

catalog the gamma rays according to their energy distribution and this is the basis for *scintillation spectrometry.*

Response of Sodium Iodide to Gamma Rays

Some of the gamma rays interacting with a sodium iodide crystal are completely absorbed, others transfer only part of their energy to the crystal, and still others penetrate completely through the crystal. Almost all gamma rays of low energy are absorbed, but many less gamma rays of high energy are absorbed. This energy distribution and consequent variations in the intensities of the light flashes in the crystal cause the photomultiplier to give different pulse heights.

Since we are going to talk about the height of a pulse, this term should be defined. The word pulse as we shall use it is derived from the shape of a graph where voltage varies with time. The following sketch shows a representation of a voltage that increases with time and then dies away.



This is referred to in popular electrical language as a voltage pulse. The maximum voltage that the pulse attains during its existence is called its height, and hence the height is measured in volts.

Since the height of each pulse from the crystal-photomultiplier-amplifier combination can be made proportional to the intensity of the light flash in the crystal, we can record the pulses according to their height and arrive at a distribution of the energies imparted to the crystal by the many gamma rays interacting with it. Such a graph is called an energy or pulse-height spectrum.

The Pulse-Height Spectrum. – The various radioactive isotopes that are used medically eject gamma rays with certain characteristic energies, rather than a whole continuous range of energies. For detection purposes, we might be interested in concentration on one of these gamma rays, especially on one that has enough initial energy to penetrate a patient's body and still be detected by the crystal. We have no assurance that, when several gamma rays leave a source with the same energy, they will arrive at the crystal in the same state. Modification of their original energy takes place as a result of interactions with the material through which they pass.

Furthermore, gamma rays interact with sodium iodide in a manner basically similar to that for all other matter. The observed response of sodium iodide to gamma rays of a single energy, however, is rather complicated. But since sodium iodide is a special kind of matter, in that we can actually see evidence of the interactions, we can interpret correctly not only the response of sodium iodide to gamma rays but any modifications in the character of the gamma rays from the patient. In order to analyze this visible evidence of interactions in both the crystal and source, we must utilize a special kind of graph, called a *pulse-height spectrum.*

A pulse-height spectrum shows the number of pulses in a given pulse-height interval; for example, it might show how many pulses were observed in a given time having heights of, say, from 10 to 15 volts, or any other interval we choose. This special graph is a little different from the types we come into contact with in everyday life. To understand how it is different, let us plot a "spectrum" of a quantity with which we are more familiar. From census figures we can determine the number of persons in the United States having ages zero to five years. Similarly, we can find the number in every five-year interval, representing the population of the United States. The correct way to plot a graph with such information is shown in Fig. 3. Note that the vertical axis is labeled in units which define the

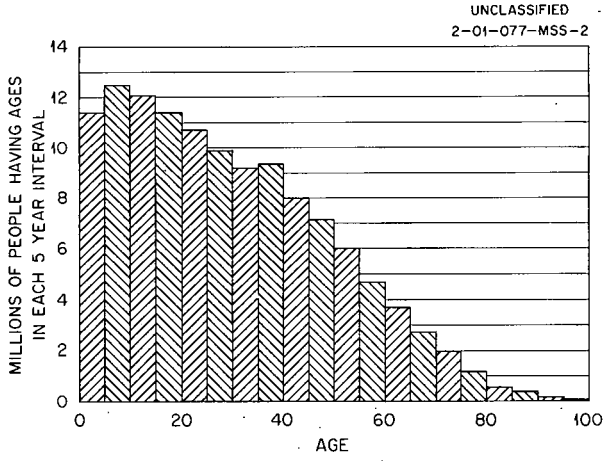


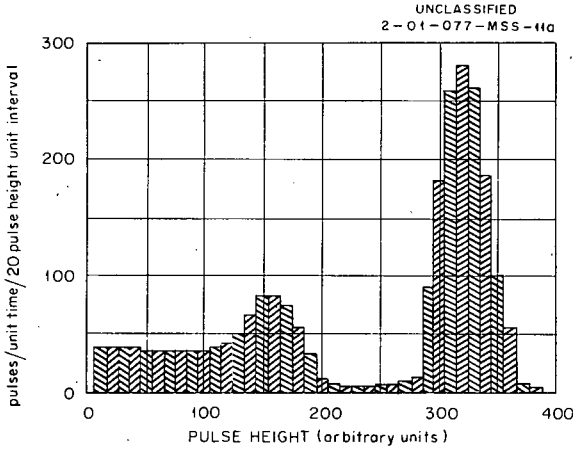
Fig. 3. Bar Graph or Histogram Showing the Numbers of Persons in Certain Age Groups in the U.S. (1930) or "The Distribution Function of Age of People in the U.S."

age interval chosen. Note further that we can add up the numbers of persons in each group over the whole age range and arrive at the total population of the country. We can do the same thing for pulse height. Instead of grouping the persons according to age, let us group pulses according to height. Such a graph is shown in Fig. 4*a*. It is more common, however, to use dots at the lower edge of the pulse-height interval or at the center of the interval to plot the distribution. Such a graph is shown in Fig. 4*b*.

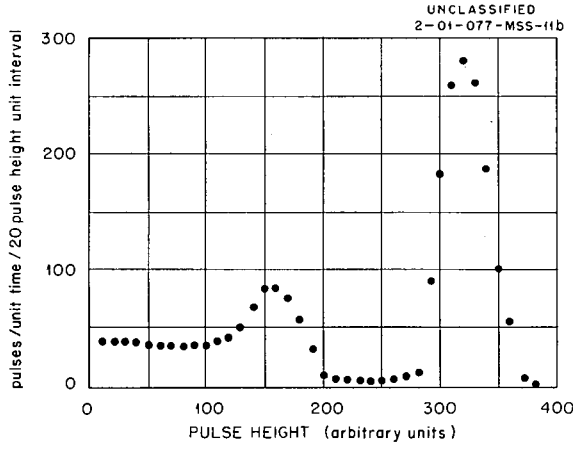
From experience it has been found that the pulses have considerable variation in height for a particular spectrum, and it is best to plot on semilogarithmic coordinates (see Fig. 5). This modifies the vertical scale and makes the peaks that occur with low intensity more outstanding. In addition the shapes of the peaks are easy to draw on semi-log coordinates and this aids in the analysis of the spectra.

Note in Figs. 4 and 5 that the counting rates were plotted against pulse height. These pulse-height units are arbitrary and can have any value that we wish. Most often they actually represent the pulse height in voltage since most of our pulse-height-measuring equipment operates on a voltage comparison basis. The horizontal axes of spectra, however, can be thought of as representing either voltage or energies in kev or Mev. Quite often we find it convenient to adjust our pulse-height-measuring equipment so that, for example, 10 volts might represent 100 kev. This makes a proportionality between arbitrary pulse-height units and energy that can help remove much of the difficulty in understanding spectra. In these notes most of the spectra are plotted against pulse-height units, but you will note that in some cases pulse-height units equal kev.

The Spectrum Utilized to Explain Reactions in the Crystal. – As a further description of how a spectrum may be utilized, see Fig. 6. This is a smoothed actual spectrum of cesium-137 gamma rays on a $1\frac{1}{2}$ inch by 1 inch NaI (sodium iodide) crystal taken with a scintillation spectrometer. The point at 700 counts/sec and 660 pulse-height



(*a*)



(*b*)

Fig. 4. Histogram Showing (*a*) Number of Pulses in Certain Height Groups Resulting from Chromium-51 Gamma Rays on NaI (Pulse-Height Spectrum of Chromium-51 Gamma Rays on NaI); (*b*) Histogram (Using Points in Center of Pulse-Height Interval Instead of Bars) of Chromium-51 Gamma Rays on NaI.

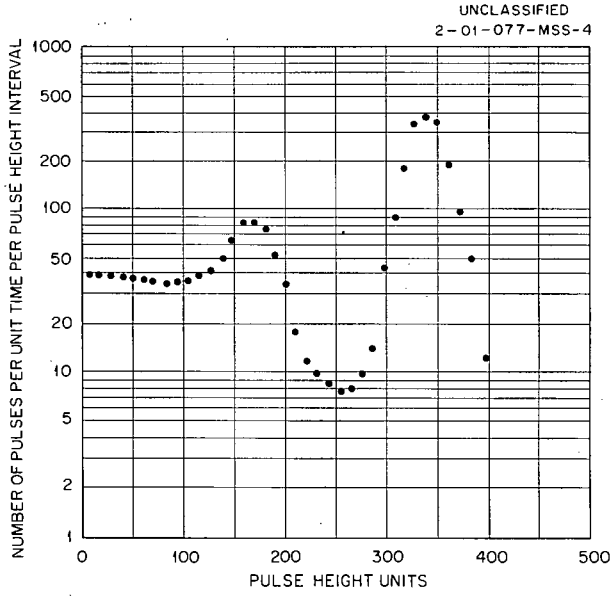


Fig. 5. Pulse-Height Spectrum of Chromium-51 Gamma Rays on NaI (Fig. 4 Replotted on Semilog Coordinates).

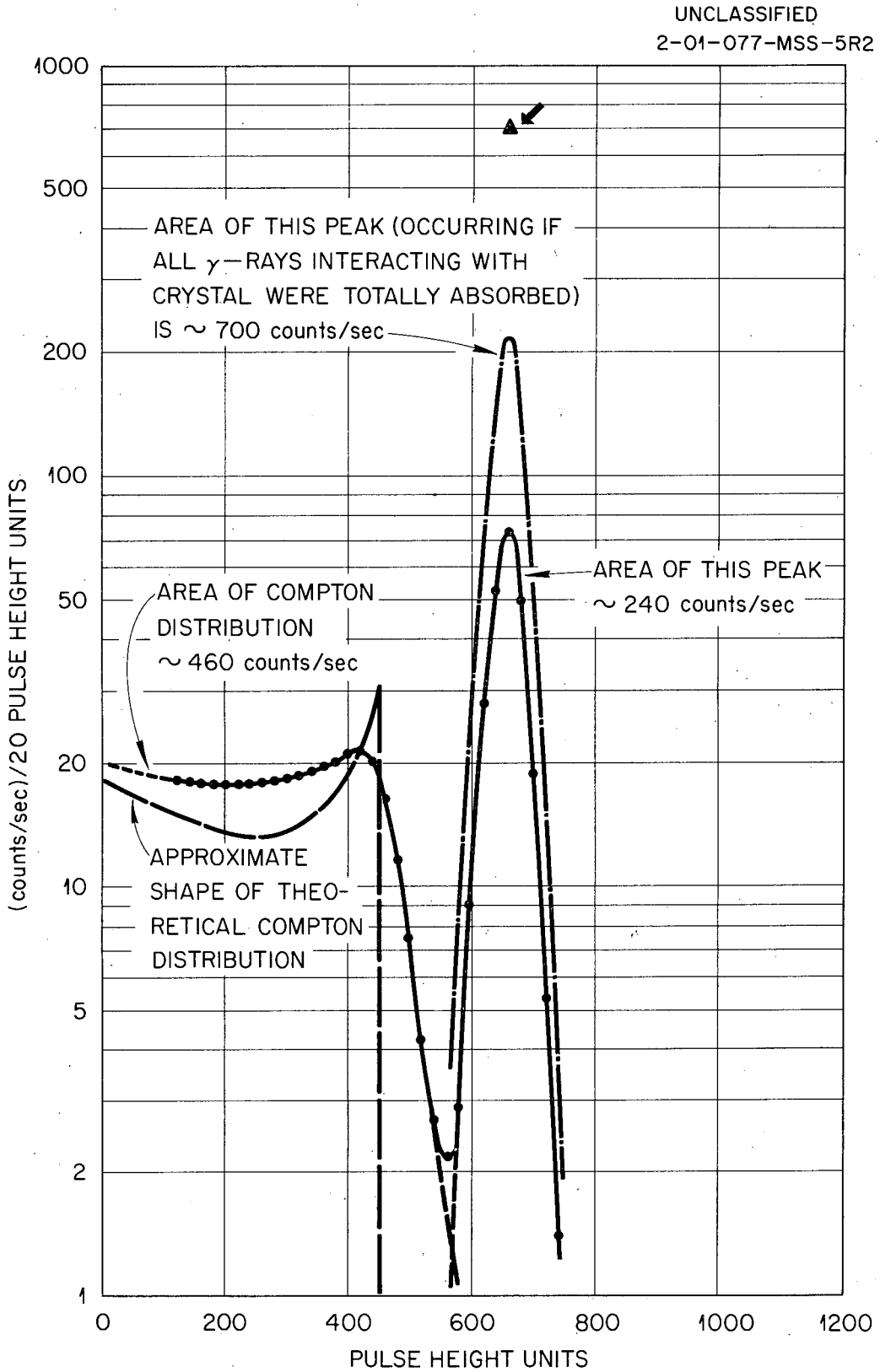


Fig. 6. Smoothed (Neglecting Ba K X Ray and Scatter) Cesium-137 Gamma Rays on $1\frac{1}{2} \times 1$ Inch NaI Crystal. Counts/sec versus pulse height. Total counting rate approximately 700 counts/sec.

units would be the result of monoenergetic gamma rays falling on an NaI crystal and photomultiplier of perfect resolving power if all the gamma rays interacting with the crystal gave up *all* their energy to the crystal. In other words, this point represents total absorption of the gamma rays since all the electrons set in motion by the gamma rays would be stopped in the crystal and thereby cause the crystal to emit light flashes. The entire spectrum would consist of this point. Because of the spread or "splatter" in pulse heights caused by an actual crystal and photomultiplier, we would have a *total absorption peak* centered at 660 pulse-height units. The area under this peak, in other words, the total number of counts, would be 700, the same as the value of the single point. The difference is that the counts have now been spread over the large area enclosed by the curve, as shown by a dot-dashed line.

We have already stated that not all the gamma rays interacting with the crystal give up all their energy to the crystal. In fact, at a medium gamma-ray energy (250 kev to 2 Mev), a Compton scattering interaction is by far the most likely event to happen to the gamma ray. Much of the time the scattered electron is all that is stopped in the crystal – the recoiling gamma ray escapes. (If we add together the energies of the stopped electron and the escaping gamma ray, they would equal the energy of original gamma rays that cause the event.) Therefore, there is a group of pulse heights that result from these partial transfers of energies to the atoms of the crystal. The shape of the theoretical spectrum from the Compton scattering events is shown in Fig. 6 as the area under the long dashed lines which drops abruptly at 450 pulse-height units. The smooth curve, often called the *Compton distribution*, is the actual spectrum obtained. This Compton distribution subtracts from the total absorption peak. Instead of there being 700 counts/sec in the total absorption peak, there are only 240, because the remaining 460 resulted only in Compton interactions in which the recoil gamma rays escaped. The choice of a crystal size is strongly influenced by these facts and will be discussed later.

Since it has been stated that the Compton process is by far the most likely first event for "medium" gamma ray energies (which encompasses practically all gamma-ray energies from radioisotopes in medical use), how is it that the area of the total absorption peak in Fig. 6 is as large as it is compared with the Compton distribution? The answer is that most total absorption peaks result from a complete transfer of energy from the incident gamma ray to the crystal by repeated Compton scattering events, in which the recoiling gamma rays do *not* escape the crystal. The final event is a swallowing-up of the last recoil gamma ray in a photoelectric process. This reaction occurs so rapidly that all the individual flashes of light from the scattered electrons combine into one large flash as seen by the photocathode. Going back to our billiard ball analogy – the cue ball makes a strike on a table of many balls. Several balls are set in motion, rattle around the table, and each finally drops into a pocket. If none of these balls jump off the table, then the total energy expended by many balls coming to rest is the same as that given to the cue ball.

Examples of the two foregoing cases are shown in Fig. 7. Figure 7*a* depicts what might happen in a Compton scattering event. A gamma ray enters the crystal, giving part of its energy to an electron, and the recoil gamma ray escapes the crystal. Luminescence is formed because the electron gives up its energy to the crystal by successive collisions with the crystal atoms. In this case, the intensity of the light flash is a fraction of that representing the energy of the incident gamma ray, since only the energy of the scattered electron is imparted to the crystal.

Figure 7*b* shows how the total absorption of the incident gamma ray could result from repeated Compton scattering events followed by a photoelectric process. In this situation a gamma ray enters the crystal and causes a Compton scattering event. The recoil gamma ray does not escape but causes another Compton scattering event. The second recoil gamma ray might be captured in a photoelectric process. Note that in this case all the energy of the gamma ray has been imparted to the crystal and that the combined intensities of the light flashes result in a photomultiplier pulse representing the total energy of the incident gamma ray.

Pair production occurs at high energies, and such spectra show three peaks (see Fig. 8). When the positron is destroyed (described in "Interaction of Gamma Ray with Matter") two 511-kev gamma rays result, and one, or both, of them might escape the crystal. The 2.76-Mev peak of the Na^{24} spectrum represents the combined energy of the electron and the absorbed 511-kev gamma rays. The 2.25-Mev peak results from those cases in which single 511-kev gamma rays escape. Likewise, the double escape peak has 1.022 Mev removed from the initial gamma ray when both

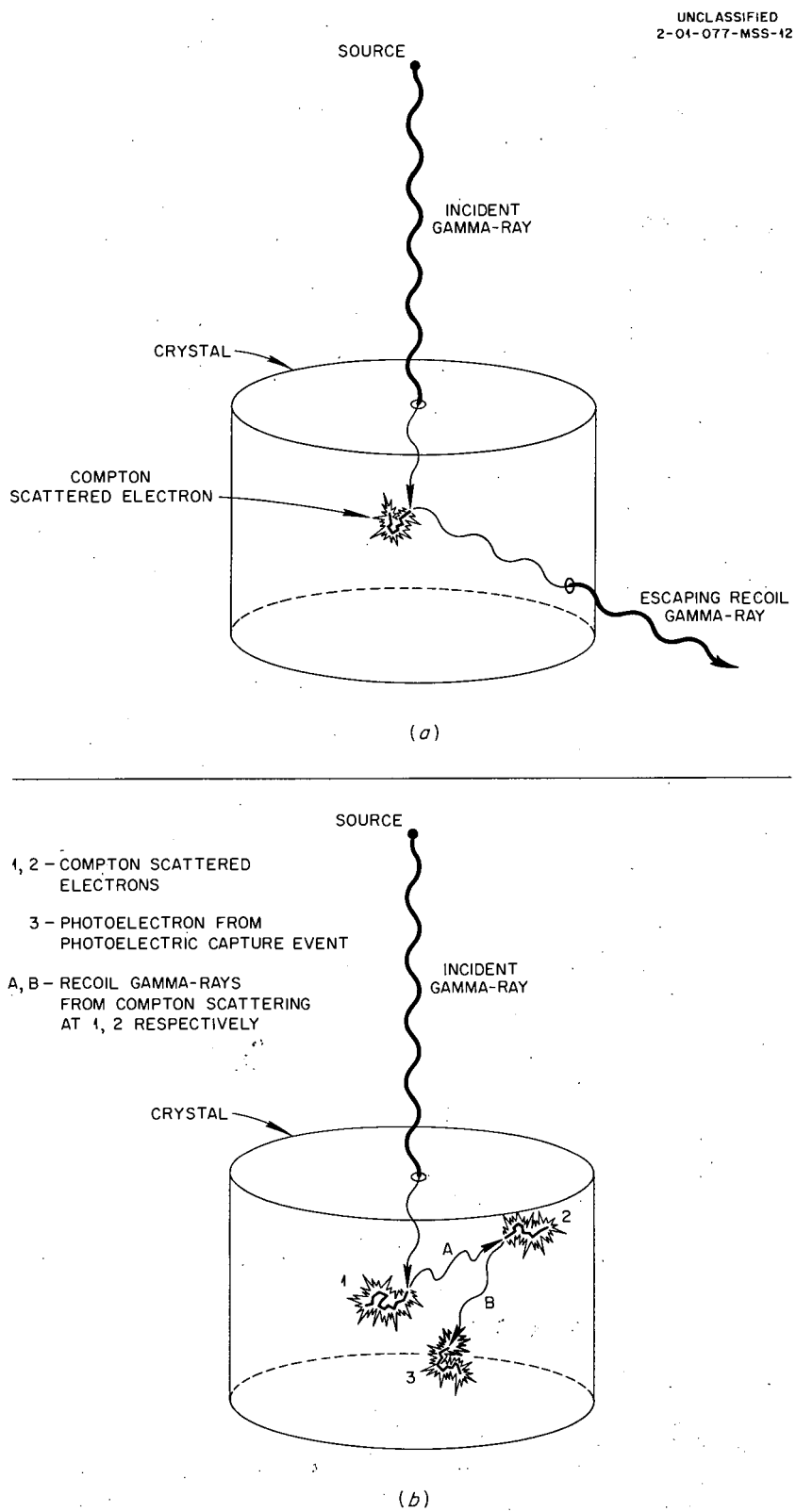


Fig. 7. Representation of Fate of Two Gamma Rays Entering NaI Crystals: Scattering Event in Which Recoil Gamma Ray (*a*) Escapes and (*b*) Undergoes Subsequent Interactions.

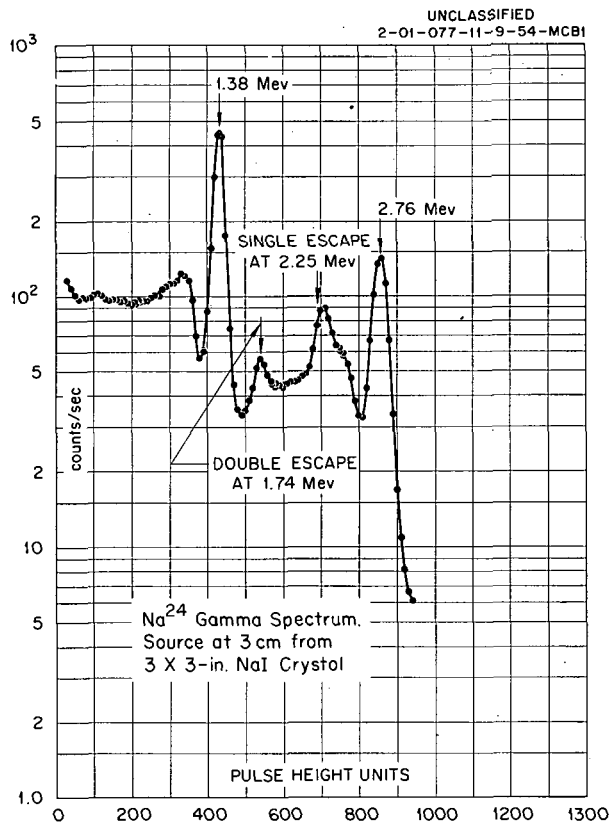


Fig. 8. Sodium-24 Gamma Spectrum. Source at 3 cm from 3 × 3 inch NaI crystal.

511-kev gamma rays leave the crystal without interacting.

At energies at which pair production is possible, > 1.022 Mev, the Compton process is still heavily contributory and the total absorption peak is made up mainly of repeated Compton processes from gamma rays that do not cause pair production.

It is pointed out that these interactions take place in the crystal regardless of how the photomultiplier output is processed. One might attempt to make all the pulses the same size by electronic trickery in order to simulate a Geiger counter. Or one might wish to preserve the linear pulse height–energy relation to the fullest. The point is that although electronic manipulations of the photomultiplier output pulses are possible, the basic happenings in the crystal are a function of the properties of the interactions of gamma rays with matter. In other words, since the pulses from the crystal are of many sizes, there is no inherent "plateau" as in a Geiger counter. One system, discussed later, attempts to provide such a plateau.

At this point it would probably be proper to say that medical use of radioisotopes rarely involves the actual plotting of spectra. It is simply being used as a descriptive tool to help the reader understand what is occurring in the crystal. Occasionally, plotting a spectrum of gamma rays from a well-known isotope with a spectrometer will ascertain the correct functioning of that instrument, but routine use of spectrometers involves counting at fixed settings in a manner quite similar to that for all but the simplest scintillation counters. This will be discussed more fully later.

The Effect of Matter Surrounding the Crystal

Extra counts are added in the Compton region of the spectrum when the crystal is in the presence of surrounding materials. These extra counts originate from three sources:

1. Gamma rays that strike the surroundings (such as a lead shield) enter the crystal with decreased energy after a Compton scattering event.
2. Gamma rays that are completely absorbed in surrounding materials cause fluorescent x rays from the material to enter the crystal.
3. Gamma rays that scatter out of the crystal enter the surrounding matter and backscatter into the crystal at a lower energy.

Figure 9 shows the first type, a 180-degree backscattering peak at about 280 pulse-height units, illustrates that two things can happen to modify our spectrum: Scattering from the surroundings of the crystal can appreciably raise the counting rate in the Compton region, and scattering peaks can confuse the identification and analysis of spectra.

The Effect of Materials Surrounding the Source

A different spectrum is obtained from a *source* (a common term used to denote the particular radioactive material under investigation) enclosed by matter as compared with the same source free from scattering material. The spectra that we have previously considered are taken from sources with low scattering, but Fig. 10 shows the effect of scattering on the 320-kev gamma rays from chromium-51 in air and in water. The dashed line illustrates the counts observed from a source immersed in water (simulating a radioactive region within a patient's body), while the continuous line is the spectrum obtained for the same source in air. Notice that the total counts (area under the curve) for the source enclosed in water have

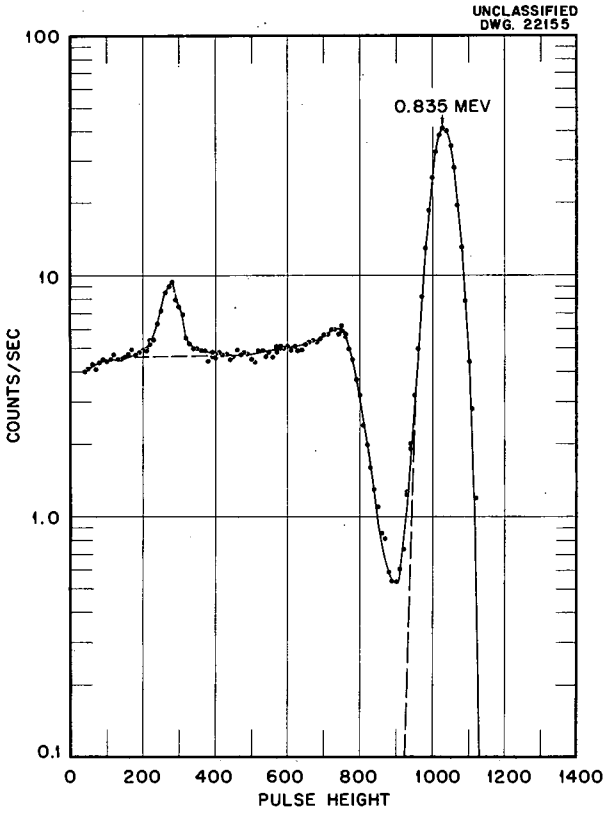


Fig. 9. Manganese-54 Gamma Rays on NaI Crystal.

increased considerably over those of the bare source. There are two main reasons for this: gamma rays that would have missed the detector are deflected into the detector; some gamma rays which would have struck the detector at their original energy are deflected but continue on into the detector at lower energy. In each case the lower energy makes for more likely detection by the crystal. This is covered more fully in "Detection Efficiency of the Crystal and the Effect of Crystal Size."

Three important conclusions result:

1. Scattering material around a source can increase its apparent strength, confusing the investigator. The same source, at the same "relative location" in different patients, can vary in its apparent strength because of the amount and shape of scattering medium.
2. Some of the gamma rays stopped in the surroundings reduce the total absorption peak as illustrated in Fig. 10.
3. The investigator can be hindered in his search for the apparent location of the source.

As a further illustration, Figs. 11*a* and 11*b* show these effects. In Fig. 11*a*, gamma ray No. 1 leaves the source and enters the crystal with the chance of being detected. Gamma rays Nos. 2 and 3 would have escaped being counted, but they happened to make Compton scattering events within the water. Recoil gamma rays 2′ and 3′ went in just the right direction to be detected. Gamma ray No. 4 was directed toward the crystal but was absorbed in the water. In Fig. 11*b*, a source outside the field of the crystal emits a gamma ray which makes a Compton scattering event within the detector's field, and the recoil gamma ray is counted.

All of these constitute obscuring factors when an attempt is being made to determine the location and intensity of a radioactive region within a patient's body. Some of the means by which these difficulties can be largely overcome are discussed in "Counting Systems."

Detection Efficiency of the Crystal and the Effect of Crystal Size

A crystal's *total* efficiency is defined as the ratio of gamma rays interacting in the crystal to those incident upon the crystal. Not every gamma ray that penetrates a crystal will interact. The probability of interacting depends on the area and volume of the crystal exposed, and the energy of the incoming gamma ray. The thicker the crystal, the greater the probability that the gamma ray will interact; the higher the energy of the gamma ray, the less probability that it will be stopped. Photoelectric reactions, for instance, are so probable at low gamma-ray energies that a small crystal is sufficient to stop such gamma rays. An example of this is 200-kev gamma rays falling on a cylindrical NaI (sodium iodide) crystal 1½ inch in diameter and 1 inch thick. Eighty-eight per cent of the gamma rays striking the crystal's surface from a source 20 centimeters away will interact. If this same source is moved within 2 cm of the crystal surface, the crystal will only be 70% efficient for the gamma rays striking its surface.

An illustration of how the change in source to crystal distance can affect the detection efficiency is shown in Fig. 12. When the source is close to the crystal (position A), gamma ray No. 1 travels through the corner of the crystal. Therefore, it penetrates very little material and is lost before it has a chance to react. An equally energetic gamma ray from the same point might make an almost perpendicular hit, encounter more sodium iodide, and interact. When the source is at position B, at some greater distance, gamma

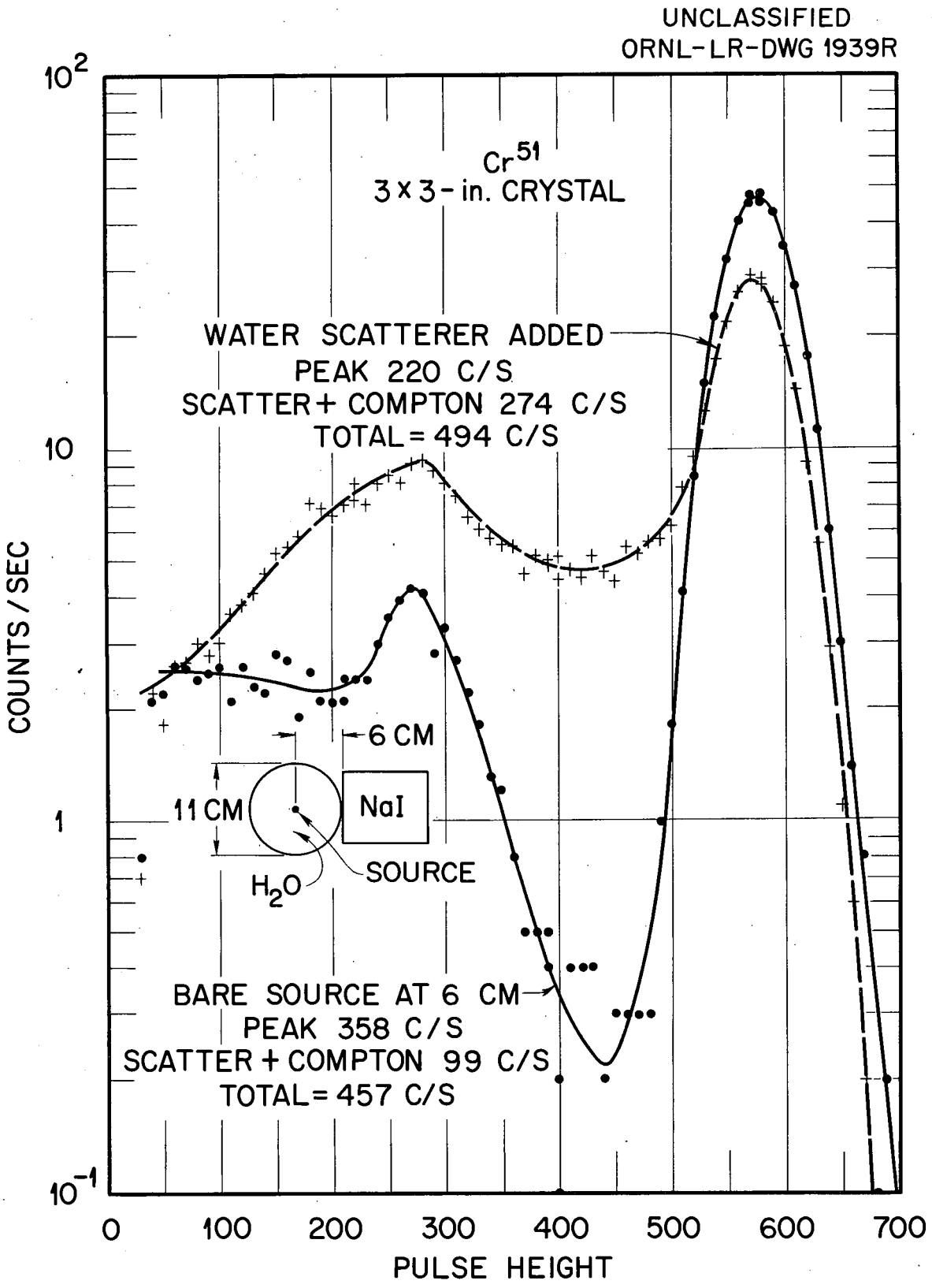


Fig. 10. Chromium-51 Gamma Rays on NaI Crystal.

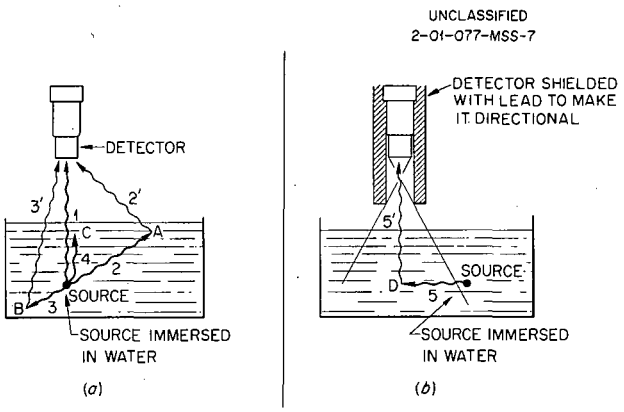


Fig. 11. Means by Which Gamma Rays Directed Away from Detector Are Deflected into Detector. (*a*) Nondirectional detector; (*b*) directional.

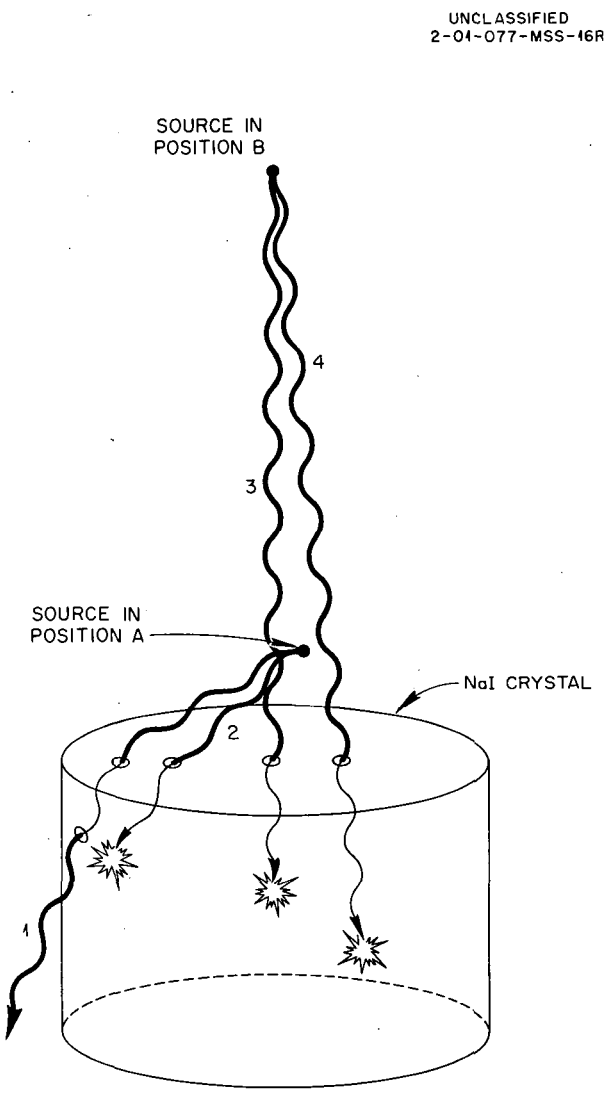


Fig. 12. Effect of Source Distance on Detection Efficiency.

rays Nos. 3 and 4 have about the same initial angle between them as Nos. 1 and 2, but now they originate far enough away to strike the crystal almost perpendicularly. Each gamma ray has a lot more crystal material in front of it and therefore has a better probability of interacting and giving a light flash. Remember also that a gamma ray escaping from a crystal has the possibility of scattering back at a lower energy. The crystal will have matter around it (packaging materials, lead shield, etc.), making it possible for reactions to occur which add to the backscatter peak.

It has been stated that a crystal's efficiency for detecting gamma rays decreases when the gamma-ray energy increases. The more energetic gamma ray has a greater probability of going all the way through the crystal without interacting. An example of this is in the $1\frac{1}{2} \times 1$ inch crystal, where at 1 Mev the efficiency drops off to between 25 and 42%, depending upon the source distance. For a larger cylindrical crystal 3 inches in diameter and 3 inches tall, the efficiency is 97 to 100% at 100 kev and reduces only to 45 to 75% at 1 Mev.

Figure 13 shows, for different source to crystal distances, how the efficiency of a $1\frac{1}{2} \times 1$ inch NaI crystal can change as the gamma-ray energy increases. Figure 14 shows the efficiency of a 3×3 inch crystal.

The total efficiency of small crystals falls off more rapidly with increasing gamma-ray energy than does the total efficiency of large crystals. This is because the greater depth of the large crystals makes it more likely that the gamma ray will interact.

Another interesting thing can be learned about the effectiveness of increased crystal size by studying the *intrinsic peak efficiency*, defined as the ratio of gamma rays totally absorbed to those striking the crystal. This intrinsic peak efficiency is plotted in Figs. 15 and 16 for various crystal sizes. As an example, look at the efficiency for 0.66-Mev cesium-137 gamma rays for two different crystals. The $1\frac{1}{2} \times 1$ inch crystal varies between 11 and 13.5%, depending upon the source distance, and the 3×3 inch crystal gives 27 to 38% efficiency for the same energy. Once again, attention is called to the fact that the higher efficiency for both crystals is associated with the greater source-to-crystal distance.

As in the case of total efficiency, the intrinsic peak efficiency decreases with increasing gamma-ray energy and the fall-off is more severe in the case of small crystals. However, the 3×3 inch

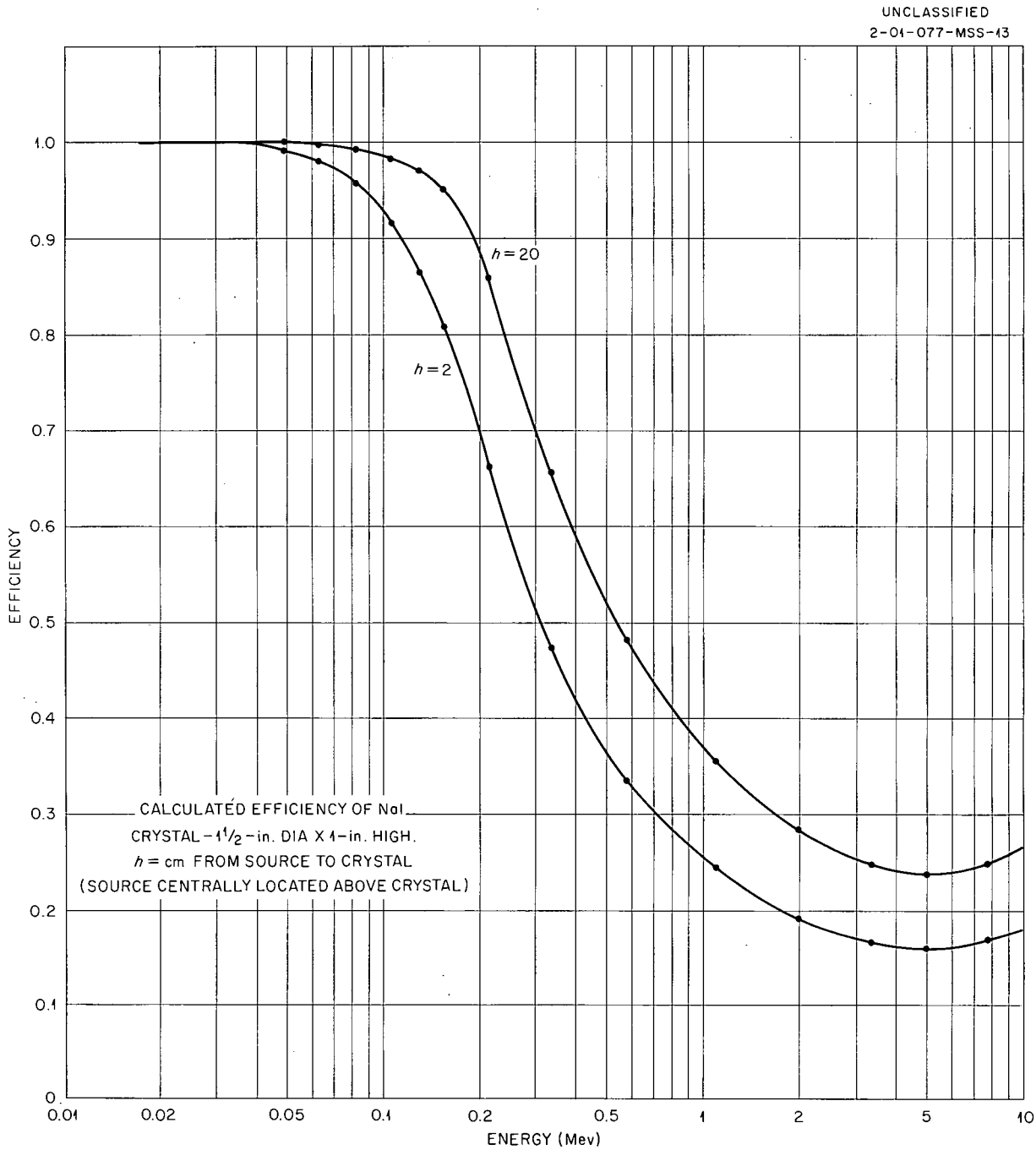


Fig. 13. Calculated Efficiency of $1\frac{1}{2} \times 1$ Inch NaI Crystal.

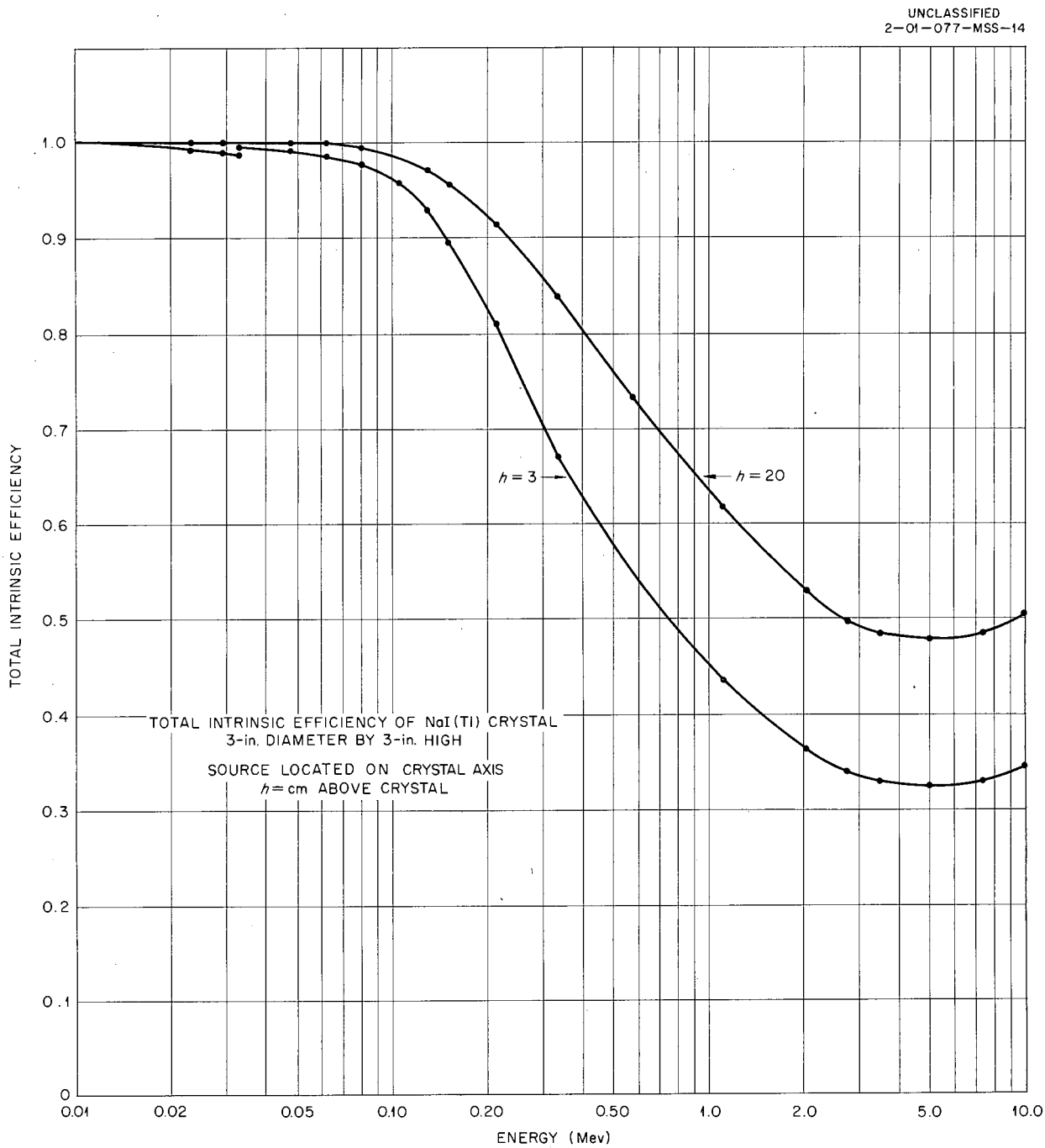


Fig. 14. Calculated Efficiency of 3 × 3 Inch NaI Crystal.

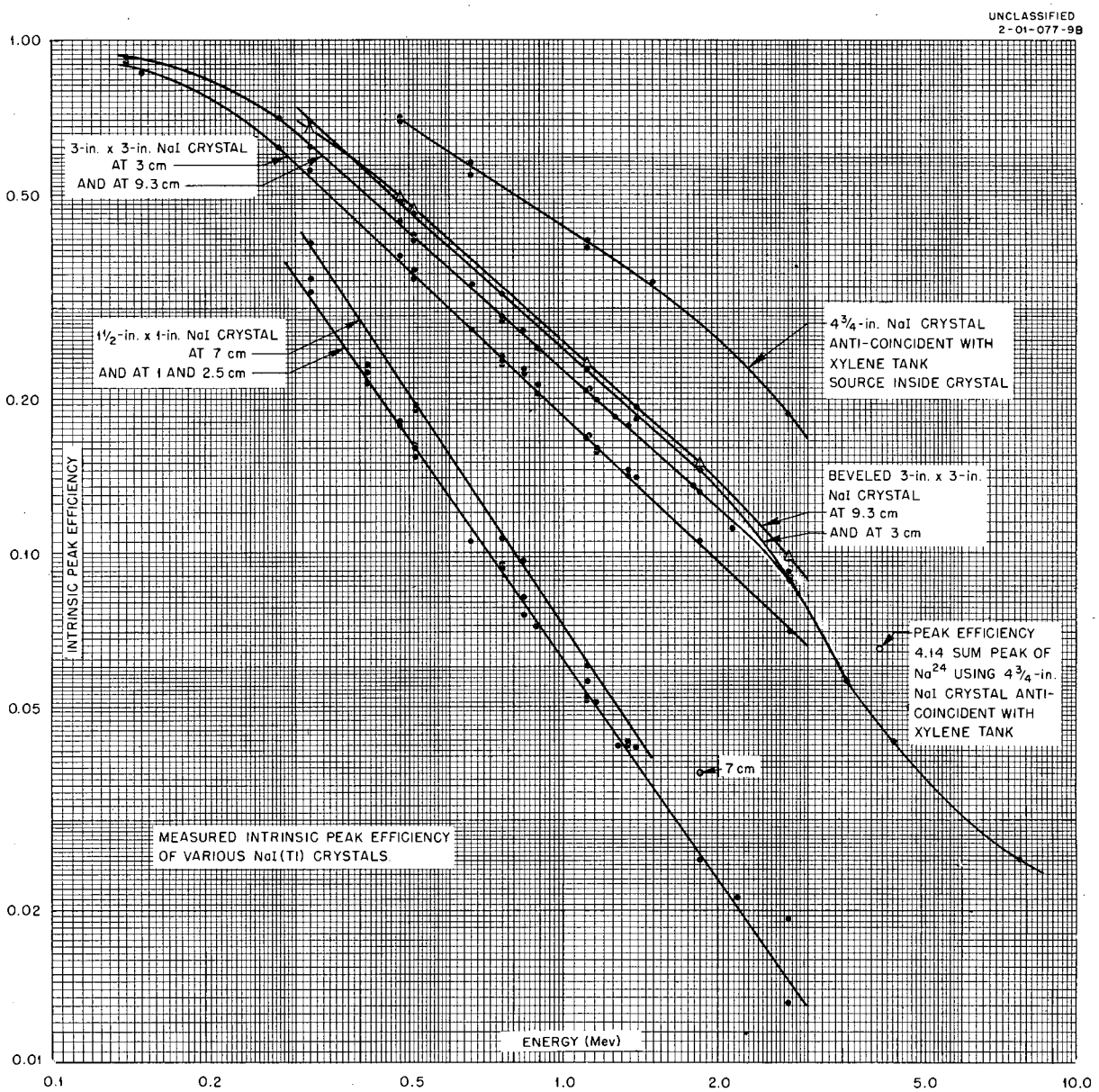


Fig. 15. Measured Intrinsic Peak Efficiency of Various NaI(Tl) Crystals.

and the 3 × 2 inch crystals are quite similar and a 2 × 2 inch crystal is nearly as efficient. This would indicate that the size of the crystal has a lot to do with its spectrum. Consider now Fig. 17, which shows the spectra observed from a source of zinc-65 subtending equal angles to a 1½ × 1 inch crystal and a 3 × 3 inch crystal. That is to say, the source is in the same geometry with respect to the crystal, for the 3 × 3 inch crystal is actually twice as far from the source as the 1½ × 1 inch crystal. Notice that with the 3 × 3 inch crystal 3150 total counts per second are observed compared with only 1710 counts per second for the 1½ × 1 inch crystal. This shows that in the same geometry the large crystal gives about 1.8 times as many counts at the same energy because of its higher *total efficiency*. However, there is another interesting comparison between crystals. In the case of the 3 × 3 inch crystal 41% (1300/3150) of the counts observed are in the total absorption peak, but in the 1½ × 1 inch crystal only 22% (370/1710) are

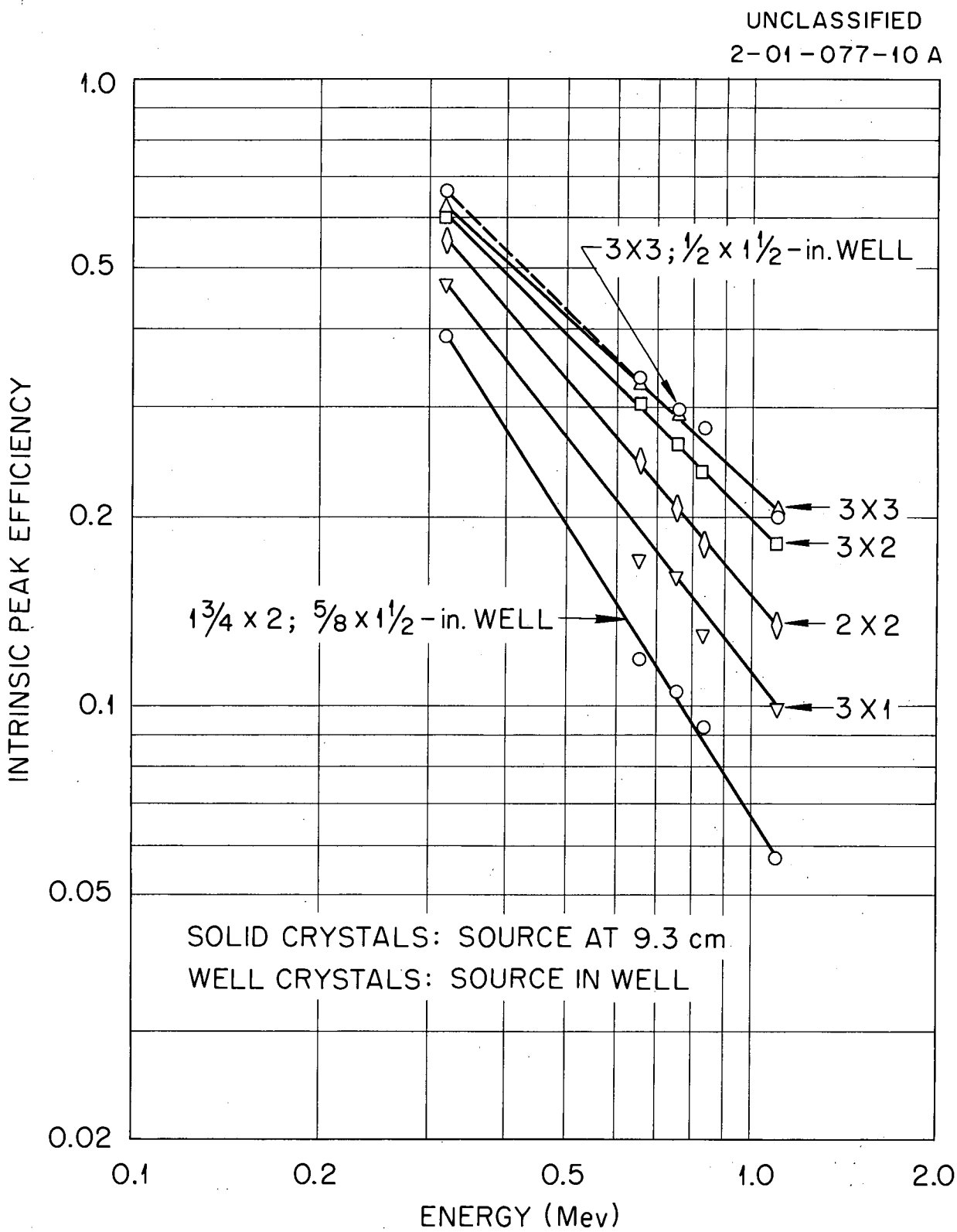


Fig. 16. Measured Intrinsic Peak Efficiency of Various NaI(Tl) Crystals.

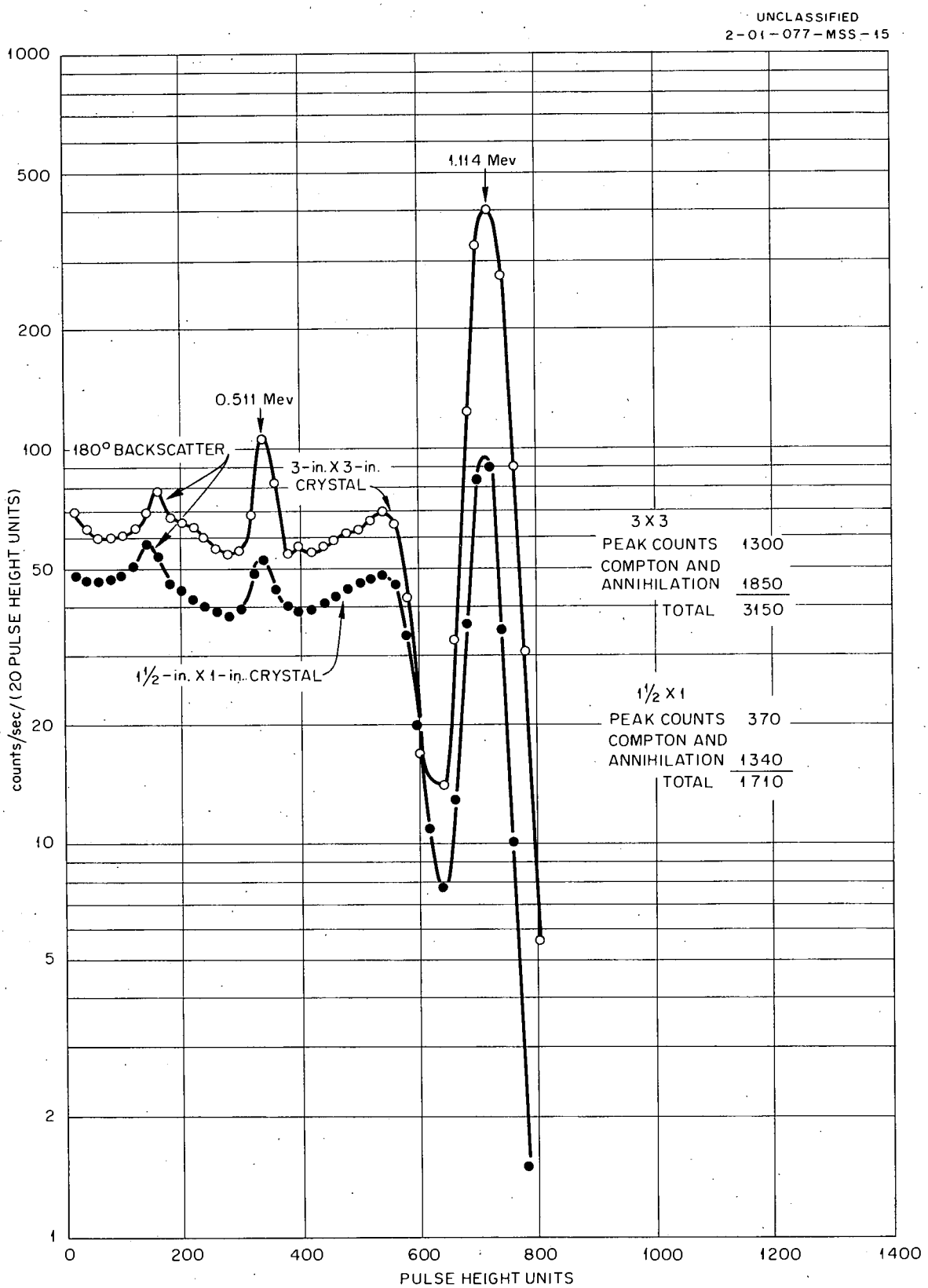


Fig. 17. Zinc-65 on $1\frac{1}{2} \times 1$ Inch and 3×3 Inch NaI(Tl) Crystals.

in the total absorption peak. This is due to the higher peak efficiency of the larger crystal. *In general, the larger the crystal, the more counts will be obtained from a given source, and furthermore, more of these counts will be observed in the total absorption peak.*

In the section "The Effect of Matter Surrounding the Source," the fact was established that the size and shape of a patient's body contribute to the amount of scattered radiation received by the crystal. For this reason, any crystal that is preferentially sensitive to low-energy gamma rays will show the largest variation from patient to patient. When any crystal is more sensitive to scattered radiation than to the primary gamma ray, it can have confusing effects for an operator trying to definitely locate and measure an area of higher activity within a patient.

Background Radiation

Always present in our environment are a few gamma-ray radiations. The scintillation counter, with its high efficiency, is very sensitive to these radiations, which originate from the following sources:

1. cosmic radiation from outer space which manages to penetrate the earth's atmosphere,
2. radiation from mineral deposits that contain the natural radioactive isotopes of the uranium, thorium, and radium families and potassium-40.
3. radiation from such sources in construction materials of buildings in which counting is done,
4. radiation from prepared or administered sources, present in the same room and in nearby storage vaults (also, radium-dial watches on persons present add to these radiations),
5. x and gamma radiation from x-ray machines and cesium-137, cobalt-60, etc., teletherapy machines.

The total result of these sources is production of an observed gamma-ray spectrum that has a relatively high counting rate at low energies, falling off with increasing energies. This is due to two things: the efficiencies of crystals are highest at low energies; and gamma radiations make many interactions with the surroundings (walls, floor, local shielding, etc.), with the result that most of the background gamma rays that strike the crystal have had their initial energy decreased by one or more scattering events. Figure 18 shows what might be a typical background spectrum on a 2 × 2 inch crystal which is closely shielded with lead on all sides but one (to reduce background) and has the face exposed. The high region at about 80 kev is partially the result of lead x rays from the shielding material. Certain small peaks tend to appear, such as the one at 1.46 Mev from potassium-40, the one at 2.62 Mev from thorium C″, and the ones from radium in structural materials. Note that the entire spectrum is mostly a smear of scattered radiation from all sources. Backgrounds in the vicinity of operating cobalt-60 teletherapy machines show the cobalt gamma-ray peaks as well as increased radiation, below this peak energy, resulting from additional scattering.

Once again, the crystal size is an important factor when considering the amount and nature of observed background. Three things result:

1. The total background counting rate of a large crystal is larger than that of a smaller crystal. However, if we take a ratio of the background counting rates for a large and a small crystal and then a ratio of their two volumes, we will find that the background ratio is smaller than the volume ratio.
2. Large crystals, because of their efficiency, do not show as great a decrease in count rate for high-energy background as do smaller crystals.
3. More of the high-energy-background gamma rays will be absorbed in the total absorption peaks in the large crystal than in the small crystal.

A high-energy gamma ray can be stopped in a small crystal, leave behind a Compton scattered electron, or cause no reaction at all. There is always the chance that this nonreacting gamma ray will still be counted, since after escaping it may strike outside materials and scatter back one or more low-energy gamma rays that will be counted. A large crystal has better stopping power for this high-energy gamma ray and increases the chance of a total absorption. No contribution is made now to the Compton distribution, which would interfere with a low-energy peak in which we might be interested. If the detecting instrument is set to see only some lower peak, the high-energy gamma ray that was totally absorbed will not interfere with the measurements.

Shielding

The radioactive dose administered to a patient is a compromise between what quantity can be safely tolerated within the body and what amount is necessary to give an appreciable count rate in the detector. This dosage is usually kept at a

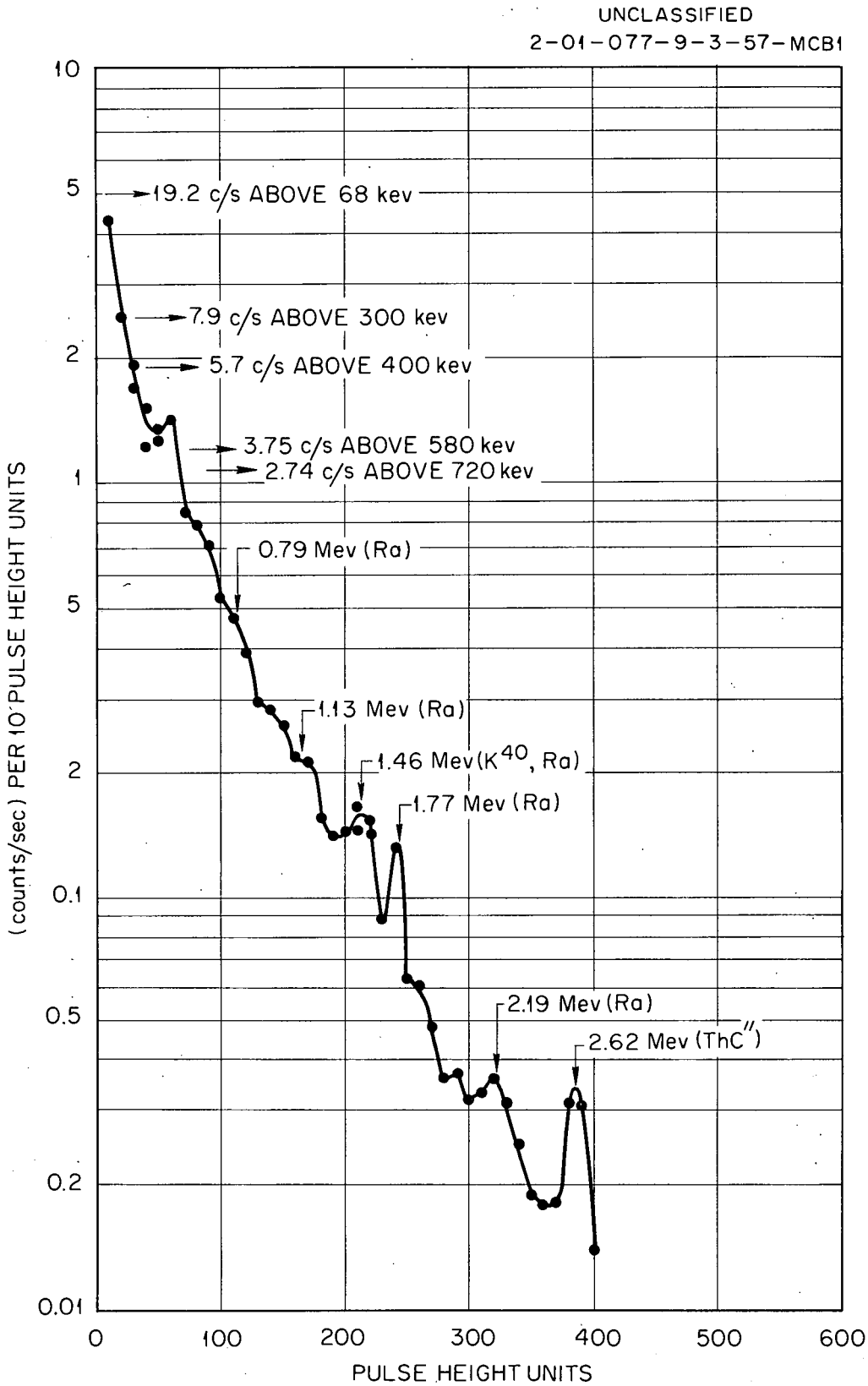


Fig. 18. Background on 2 × 2 Inch NaI Crystal in Flat-Field Collimator.

minimum, which means that we must utilize all the radiation striking the counter. A heavy background will interfere with the interpretation of our data, and dense shielding materials (such as lead) that are effective in absorbing gamma radiation must be placed around the crystal in order to eliminate as much as possible these obscuring effects. Since we desire to count radiation from the source within the patient, the directed face of the crystal cannot have shielding on it, and this unprotected side does let in some background radiation. In the case of counting a source external to a patient (such as counting the activity of a small sample of blood) we can provide shielding material which encloses both the source and the detector.

Very dense materials are required to absorb gamma radiation, and lead is commonly used although iron and solid concrete blocks can be adapted to reduce the cost. Most probing types of equipment are restricted in the amount of lead they can handle (usually not more than 1 inch), and low-level counting requires quite a lot of lead shielding. Ideally, if counting could be done in a room with thick concrete walls, with lead shielding around individual counters, and at a location remote from teletherapy or x-ray machines and from source storage vaults, the effects of background could be greatly reduced. However, in most situations the medical investigator is not so fortunate, and in some cases background radiation can be a real problem.

Certain specialized types of shielding can be placed around the crystal and photomultiplier tube to directionalize the incoming radiation (see Fig. 19). These *collimators* (so called since they collimate, or admit, gamma rays from only restricted directions) give shielding protection on the sides not directed at the source. Actually we know that it would require a large amount of material to block out all background radiation, but fortunately the majority of it falls in the low-energy region of the spectrum, and so we can prevent a lot of it from reaching the crystal with a moderate amount of shielding.

COUNTING SYSTEMS

A *counting system* consists of the following apparatus: the crystal and its shielding, the photomultiplier, and the associated electronic circuitry for amplifying, processing, and counting the pulses from the photomultiplier. The general purpose of the system is to detect gamma rays from a given source and to produce a measurement of the amount of radiation (and sometimes the physical extent and location) from the source.

There are several variations on how this detection and measurement may be accomplished using a crystal and photomultiplier. Listed below are three methods, with the names we think should be applied.

Geiger-Tube-Substitute Scintillation Counting. – The common gas-filled Geiger-tube counter (which triggers and sends out the same pulse size regardless of the gamma-ray energy) is substituted for by the *counter system.* Through electronic means an attempt is made to cause all pulses from the photomultiplier to be the same size and large enough to actuate a digital counter or a count-rate meter, both of which give the reading in counts per second.

Integral-Bias Counting. – Only the pulses higher than a certain height are counted. This often takes advantage of the fact that the crystal responds proportionally to the energy of the gamma ray stopped. All small pulses from low-energy gamma rays can be "biased" out and an *integral,* or sum, of large pulses kept. This *threshold* for counts accumulated depends upon where the operator wants to set his limit for acceptance and rejection of pulses by the instrument.

Scintillation Spectrometry. – This is similar to integral-bias counting but has the additional feature of accepting pulses whose heights lie within a restricted band. Only gamma rays resulting in pulses which attain a specified range of height are counted, and those below the threshold of admittance, or the high-energy ones above the range desired, are rejected.

Unfortunately, automatic controls cannot be incorporated into a counting system, and understanding by the operator is required in order to produce successful results. Some instruments are simple to operate in various instances (though not necessarily correctly) and are restricted in their application, while others are more complicated. Regardless of their varying degrees of complexity, all counting systems share two things in common: (1) *No instrument used ignorantly or carelessly will produce good results;* (2) *all but the lowest quality instruments will yield useful results when used with knowledge and care.*

Geiger-Tube-Substitute Counting

An attempt has been made to substitute a crystal detector for the Geiger tube because of the crystal's greater sensitivity. By doing this it was

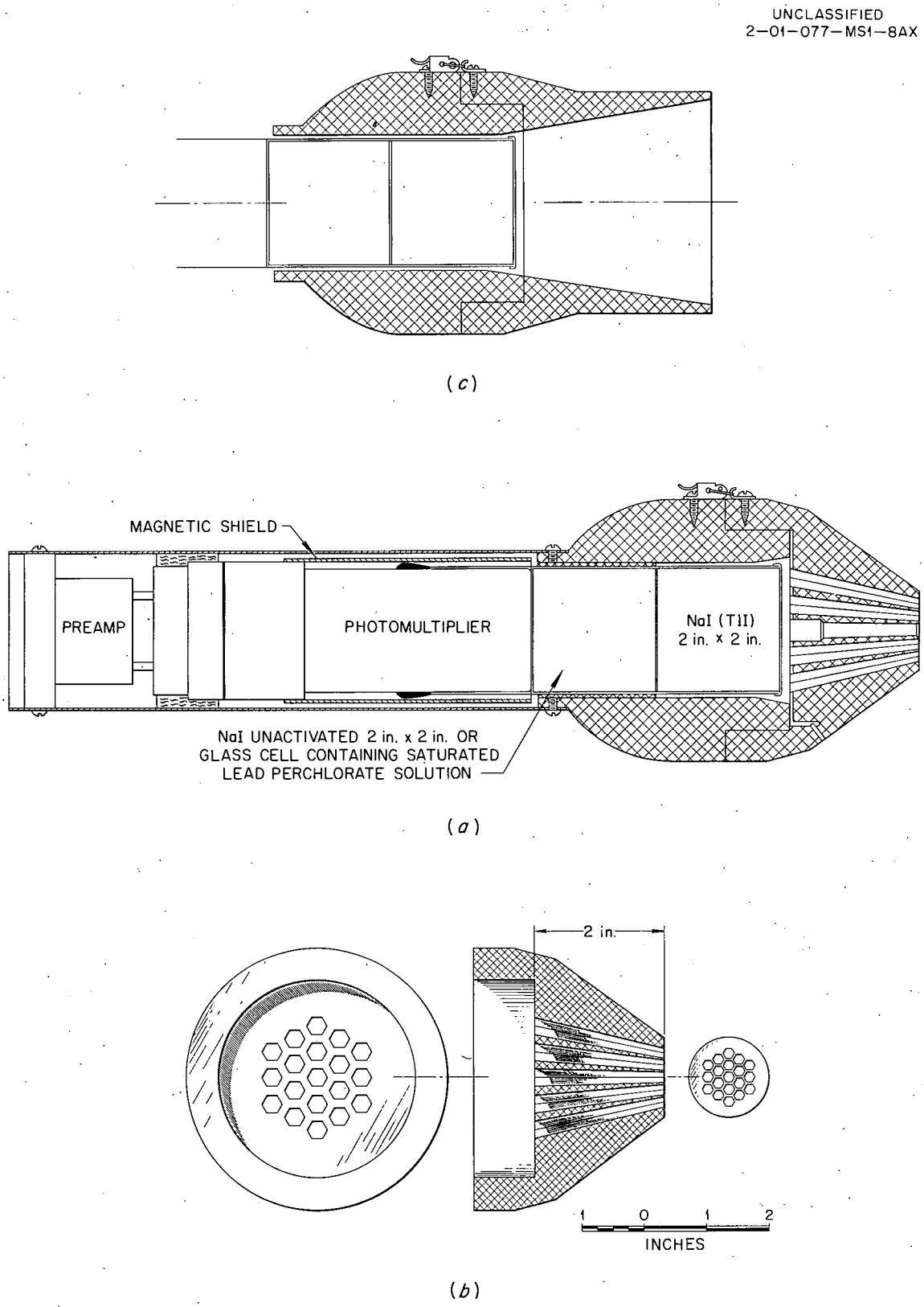


Fig. 19. (*a*) **2-Inch Probe Assembly with Focusing Collimator Attached;** (*b*) **Focusing Collimator;** (*c*) **Flat-Field Collimator.**

hoped that the dose administered to the patient could be reduced. Actually this was not exactly the case since a crystal gives the greatest counts in the low-energy region of the spectrum, picking up background and scattered radiation. This jumble of undesired counts seriously hampers conclusive interpretations of the data unless the dose given to the patient is large enough to make the source stand out above the background. The following is an explanation of how the Geiger-tube detector is replaced by a crystal and electronics, along with the limitations.

Definition and Use. – Figure 20*a* is a block diagram of the Geiger-tube-substitute scintillation counter; the labeled rectangles designate the various electronic components of the system. We have assumed the existence of a small electric power supply, as in other diagrams, for all the electronics except the high-voltage supply for the photomultiplier. The preamplifier is not always needed, but it serves the purpose of supplying power for transmitting the incoming pulse down a long cable between the detector and the rest of the instrument. A Geiger tube sends out pulses of nearly the same size after being triggered by the incoming radiation. This is duplicated electronically by the *nonlinear amplifier* and *pulse-height selector*. The crystal and preamplifier give pulses of many different heights, and the nonlinear amplifier attempts to make all the pulses the same size. The pulse-height selector examines these pulses and gives a uniform output pulse for all pulses

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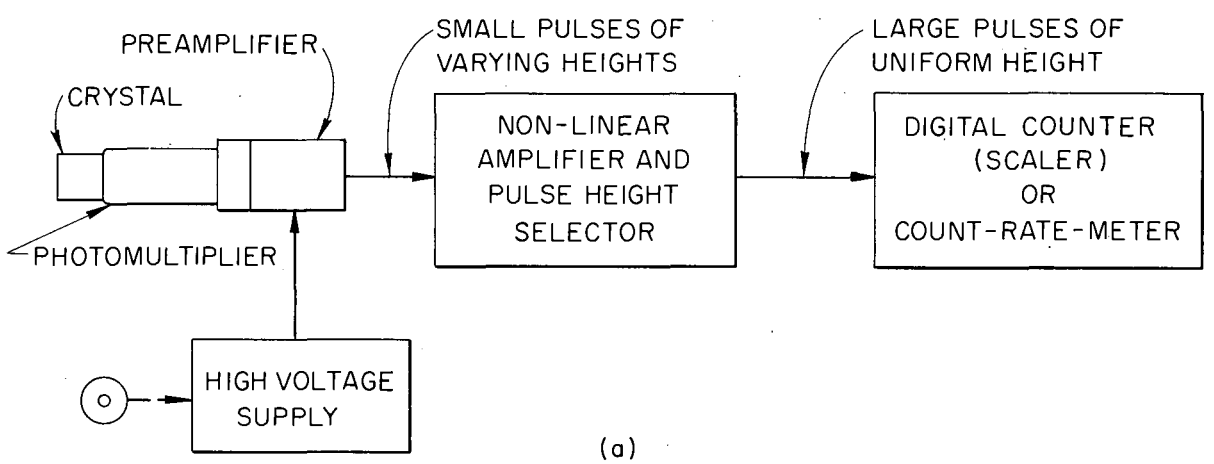
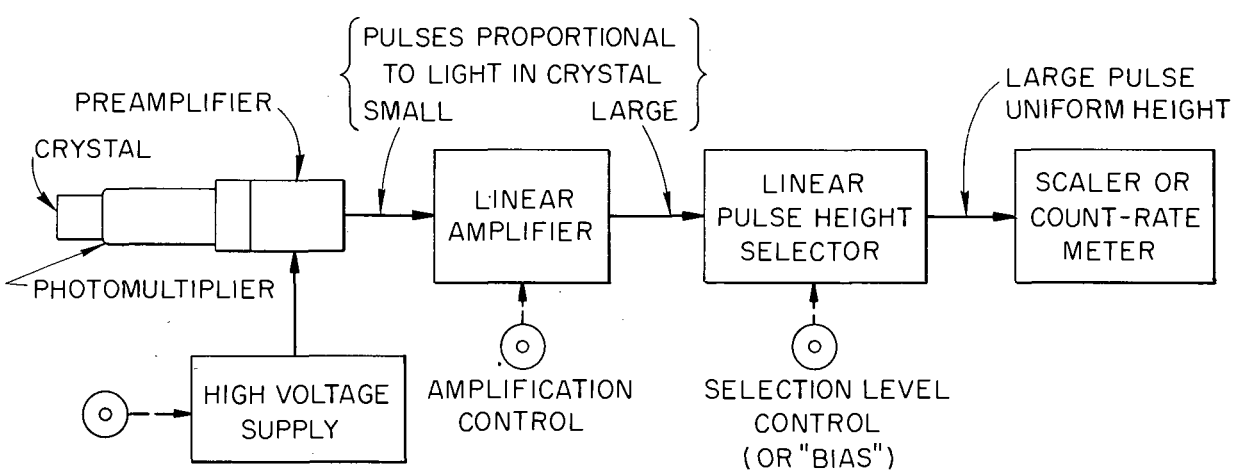


(a)

GEIGER-TUBE-SUBSTITUTE SCINTILLATION COUNTER



(b)

INTEGRAL-BIAS SCINTILLATION COUNTER

Fig. 20. Block Diagrams of Two Scintillation Counter Systems.

above a certain predetermined level, excluding those below the level. The pulses are then sent to a scaler or count-rate meter. Therefore, the pulses from the nonlinear amplifier are for the most part of uniform amplitude, but there are a few which do not receive enough amplification to bring them up to the acceptance pulse height. The pulse-height selector is usually factory-set to accept all pulses possible above the noise level of the photomultiplier.

Adjustment for Proper Use. – If the high voltage on the photomultiplier is set too low, the pulses from the photomultiplier will be so small that very few, if any, can be amplified to the maximum level and be counted. If the high voltage is set too high, then all pulses, and unfortunately including low-energy x rays and photomultiplier noise, are amplified to the maximum level and will be counted. Therefore the correct adjustment is one which causes most of the pulses resulting from the source to be amplified to the counting level.

Consider Fig. 21, which shows the variation of counting rate with high voltage in a Geiger-tube-substitute scintillation counter. (The article by R. W. Engstrom and J. L. Weaver, "Are Plateaus Significant in Scintillation Counting?" *Nucleonics* **17**(2), 70–74 (1959), is recommended to the reader.) When the high voltage is 600, only high-energy-background gamma rays produce pulses high enough to be counted. In this case they are few compared with the source gamma rays. When the high voltage is 650 (at A), only total absorption pulses are counted, but the counting rate is changing very rapidly with high voltage, and this is not a practical setting in this type of instrument. There is a plateau or region in which counting rate changes very little with high voltage, permitting a setting at B. Note that this setting records all gamma rays possible above the noise level of the phototube. The noise comes in at about 1040 volts in this example. (A 6655 phototube was used in taking these curves. However, phototubes 6291 and 6292 are in more common use, and while their gain is lower – requiring more voltage to see the peak pulses – the noise sets in relatively more rapidly with increasing high voltage.)

Note that when the source is in an environment simulating a patient the plateau is much shorter. Note also that the presence of a scattering medium makes the source appear larger and stronger than it is without the scattering medium.

Figure 21 shows how the operator (or factory) sets this type of instrument for use. In effect,

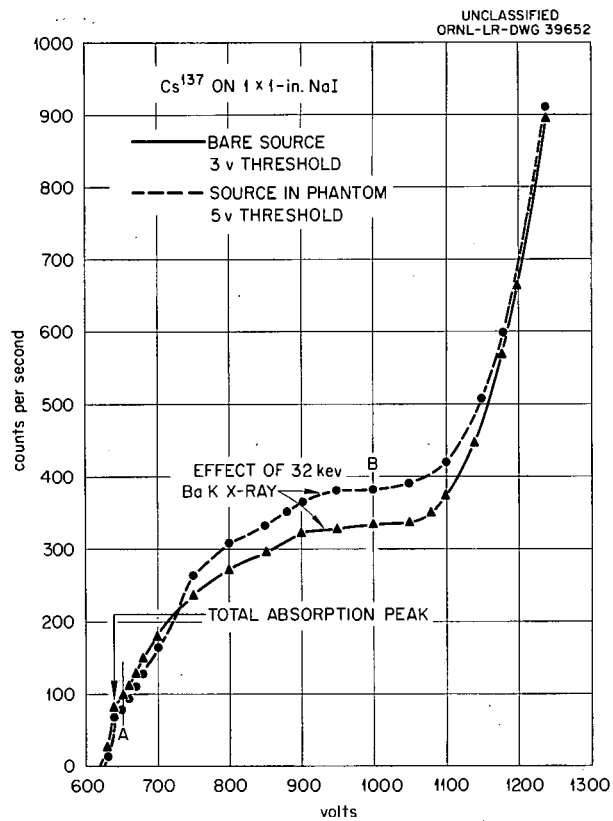


Fig. 21. Count Rate Versus Phototube (6655) Voltage.

this is the same procedure that an operator performs when he varies the high voltage on a Geiger tube for establishing a plateau. For this reason we have chosen to call this system the "Geiger-tube-substitute counter."

This instrument is considerably more sensitive than a Geiger tube for gamma-ray counting. However, it is much more preferentially sensitive to low-energy radiation. Consequently, persons using Geiger-tube-substitute scintillation counters are much more easily misled by scattered radiation. It is seen from Fig. 21 that the actual threshold is well below 32 kev. As a result, the system records all the gamma rays possible, including background. It is very much at the mercy of patient-to-patient differences in scattering. This is explained more fully in the section on integral-bias counters.

A system of this type can be simply and inexpensively constructed. An example of its application might be in determining the total counting rate of all gamma rays interacting with the crystal, such as in survey meters for prospecting and in monitoring general background levels. It also has

certain medical applications, but too often the quality of the manufactured instruments is inadequate. In an attempt to keep the cost low, very small crystals are used. We have already discussed how small crystals are most sensitive to low-energy gamma rays, including those originating from scattered and background radiation. In addition, the threshold level is generally neither precise nor readily adjustable. *It is difficult, but possible, to get accurate medical measurements with this type of system.* However, with thorough understanding of the properties of this system and with careful technique, this system (embodying good circuit design and quality components) can be made to yield useful measurements for many applications such as sample counting. TOO OFTEN THIS IS NOT THE CASE.

The Integral-Bias Scintillation Counter

Definition and Use. – The integral-bias scintillation counter is usually more complex and more expensive than the one described above, but it can yield very good results when properly used (see Fig. 22). Instead of having the nonlinear amplifier to equalize all the pulse heights, we could substitute a *linear amplifier*, which increases the height of each pulse leaving the photomultiplier

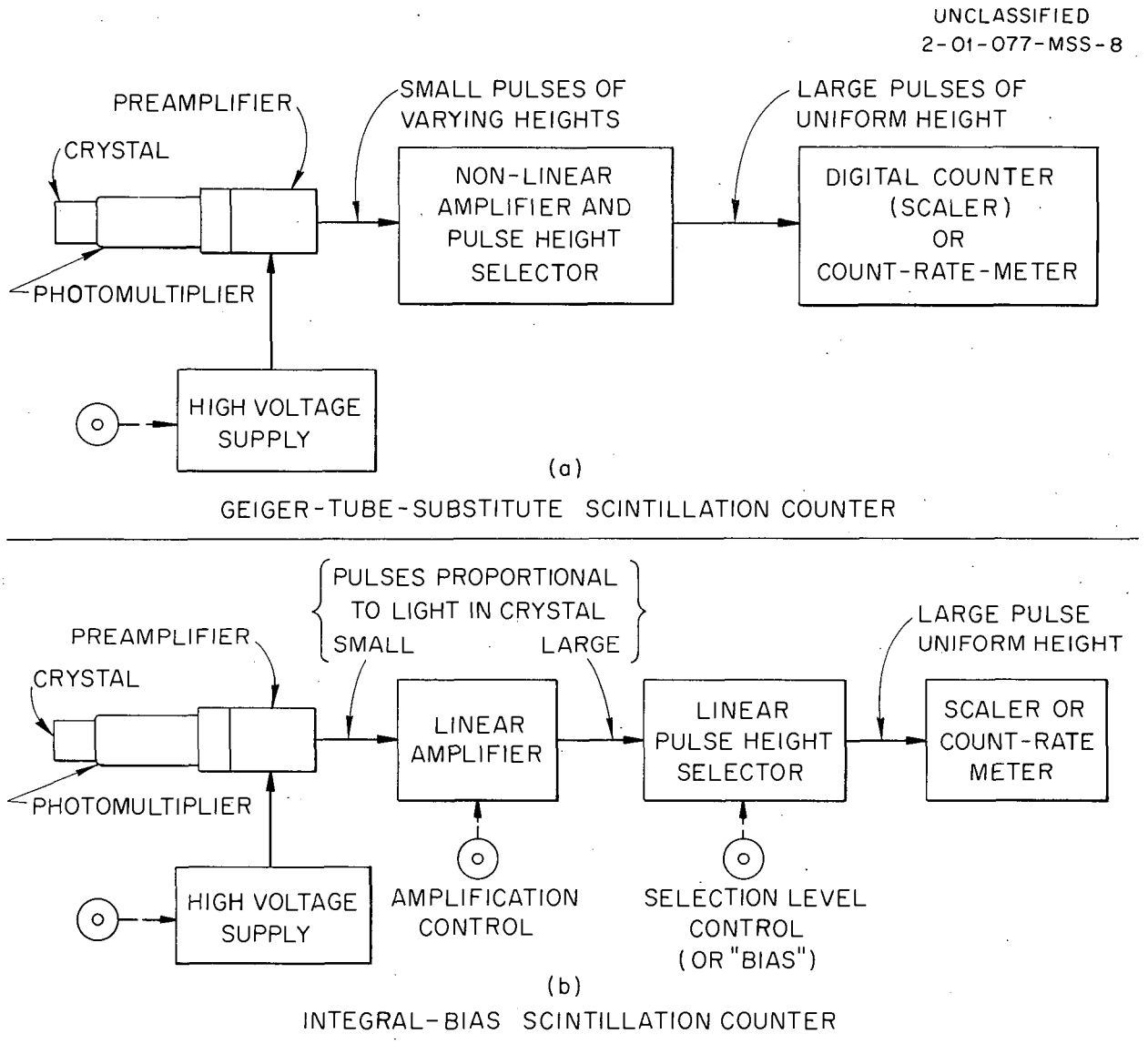


Fig. 22. Block Diagrams of Two Scintillation Counter Systems.

proportionately. These amplified pulses are necessary in operating the electronics because the pulse leaving the photomultiplier (which itself is proportional to the energy transferred to the crystal by the gamma ray) is still too small for effective use.

Again we have added a pulse-height *selector* to examine the pulses from the amplifier. This is adjustable so that the operator can set the instrument to reject all small pulses below a desired height while passing the rest on to the scaler or rate meter for recording.

The pulse-height spectrum for 320-kev chromium-51 gamma rays in Fig. 23 gives a representation of how the pulse-height selector can be used for greater accuracy. The curve through the solid circles is for the bare source in air. The curve for the open circles is for the source placed in water to simulate the material composition of the patient's body through which the gamma rays must pass. This introduces a lot of scattered radiation, as indicated by the rise in the Compton distribution and a reduction in the total absorption peak. The effect of placing a lead filter between the source and crystal is indicated by the curve through the triangles. Many people use a 2-millimeter lead shield over the face of the crystal in an attempt to remove the effects of scattered radiation. It is not clear how much the lead helps us, for we have added to the spectrum a large 80-kev x-ray peak from the lead. Let's see how the pulse-height selector can improve on the situation.

Suppose that at first we set our pulse-height selector at position A-A on the graph. This will reject all counts of lower pulse height than that represented by the dashed line and will count everything above it. Almost the complete spectrum is being accepted, and a great many background counts which predominate in the low-energy region are being registered. In addition, the Compton distribution region, which is composed largely of low-energy gamma rays and scattered radiation, is being accepted. These extraneous counts will distract from the desirable information – the total absorption peak which represents radiation directly from the source. (The Geiger-tube substitute also counts the maximum energy range with similar or even lower settings.)

Now let us move the pulse-height selector to position B-B, at 600 pulse-height units. All the counts in the shaded region are rejected electronically, while those in the total absorption peak and the few remaining above are counted. Also, we no longer need the lead filter which reduced the total absorption peak while not necessarily eliminating the scatter. When we reject scattered radiation by electronic means, the total count rate is reduced no more than by a 2-millimeter lead filter over the crystal face.

The operator in this case sets his instrument by using a "bare source" (one with no shielding material), then adjusting the pulse-height selector to accept pulses at 600 units in height and over and reject the lower ones. However, without a differential plot, or considerable experience, a person would find setting this counter confusing. The integral-bias counter cannot be used to give a *differential* plot directly but we can use it to obtain an *integral spectrum* (see Fig. 24). These two different plots are distinguished in the following manner: each point on the differential spectrum represents the number of counts per unit time found in a particular pulse-height interval. On the integral plot, each point on the spectrum represents the total counting rate for all pulses coming into the instrument above the selected pulse-height setting. For example, in Fig. 23 the bare-source curve (solid circles) shows that there are about 290 counts in the pulse-height interval between 750 and 770 pulse-height units. Any other position along the spectrum will likewise show some count rate in the denoted pulse-height interval only. Switching to the integral curves in Fig. 24, a pulse height of 600 units here gives a rate of about 2900 counts/sec (on the source-only curve) because at this setting we are counting all pulses whose height is 600 units and over.

Correspondingly, the rate for all pulses 100 units and above is 4100 counts/sec, and the rate for pulses 900 units and over is zero. Notice also in Fig. 24 that at 600 pulse-height units the count rate is rising only slightly with the diminishing pulse-height-selection level. This may be expected when we refer to Fig. 23 and notice that at 600 pulse-height units we are set in the trough between the total absorption peak and the Compton distribution peak.

Adjustment for Proper Use. – The differential and integral spectra discussed above showed a method of setting the pulse-height-selector level at the proper place in order to reject scattered radiation from a source. An operator may adjust his instrument for a source emitting a monoenergetic gamma ray such as chromium-51 as follows:

1. Increase the pulse-height selector (PHS) setting until all the counts from the source are rejected, which means that all the pulses originating

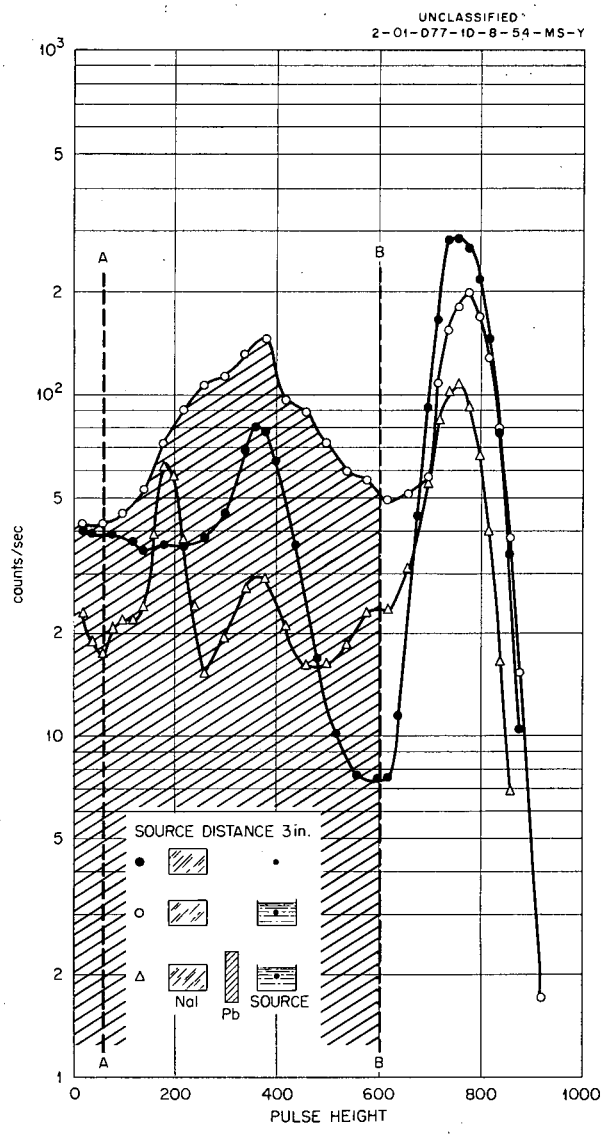


Fig. 23. Pulse-Height Spectrum of Chromium-51 Gamma Rays on 3 × 3 Inch NaI Crystal Under Three Conditions.

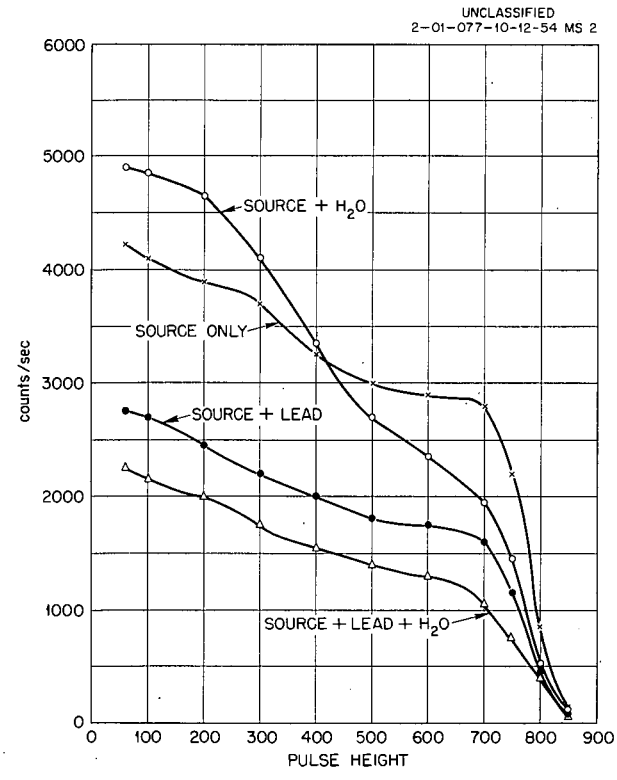


Fig. 24. Integral Pulse-Height Spectrum of Chromium-51 Gamma Rays on 3 × 3 Inch NaI Crystal Under Four Conditions.

from source radiation are below the selection level, a setting comparable to a PHS setting of 900 in Fig. 24.

2. If counts from the source are still coming through when the PHS level is set at maximum, then the pulse heights are too great and must be reduced. This is accomplished by reducing the amount of amplification or by reducing the high voltage which reduces the size of the photomultiplier output pulses. Reduce either one or both until no source counts are obtained with the PHS level somewhere below maximum.

3. Now slowly reduce the PHS setting and observe the increase in counting rate as the level of the largest pulses due to the source is reached. An operator might observe a count-rate meter (or the flashing of scaler lights, the tapping of a mechanical counter, or an aural count rate indicator) to obtain some indication of counting rate.

4. Continue to reduce the PHS setting as the counting rate increases rapidly (corresponding to the 700 to 800 pulse-height region in Fig. 24). Then continue past the region of rapid increase into that where the counting rate increases slowly. This corresponds to the region of 550 to 650 pulse-height units in Fig. 24. A setting of 600 PHS units would be best in this case. With an understanding of the basic principles and with practice, satisfactory adjustments become easy. These must, of course, be done separately for each isotope used.

Once the instrument is set, the measurement of a source in a patient can be properly made even though the integral spectrum of a source in a patient appears as the "Source + H_2O" curve in Fig. 24.

Geiger-tube-substitute scintillation counters are usually factory-set at even lower than the 60-unit point in Fig. 24. Note that the setting includes all

the effects of scattered radiation as well as all the background. Note also that a source can give more counts than it should, as was shown in Fig. 21 (compare also the "Source Only" and the "Source + H_2O" curves in Fig. 24).

Note that with a PHS setting of 600, about 2350 counts/sec are obtained on the "Source + H_2O" curve. If a setting of 60 and a lead filter are used, about 2250 counts/sec are registered. Therefore the use of the integral-bias counter can provide an answer more free from scattering than the Geiger-tube-substitute counter, *with no reduction in net counting rate* (total counts minus background.)

Background Reduction. – With an integral-bias counter, the observed background is a fraction of that from a Geiger-tube-substitute counter (one-fourth in the example of Fig. 24). This results from the use of a relatively high PHS level (600 units in the example of Fig. 24), thereby eliminating most of the background. As a result, a smaller dose can be given to the patient (one-fourth in this case).

Incidentally, a manufacturer's claim of a certain background for a counter apparatus is often meaningless since the observed background results from four things, the first of which is not under the control of the manufacturer:

1. amount of background radiation actually present in the counting location,
2. pulse-height selector setting,
3. crystal size,
4. shielding.

It does make some sense for a manufacturer to claim a low background for a shielded counter, because it is some measure of the merit of the shield, but to put a definite number on it is meaningless.

The Scintillation Spectrometer

Definition and Use. – The scintillation spectrometer is quite similar to a top-quality integral-bias counter but has one very important addition: another pulse-height selector (or discriminator) has been added for the rejection of pulses higher than a certain level. Now we can use the lower PHS as before to reject counts below a certain pulse-height level and set the upper PHS to exclude those counts above a desired level, as shown in Fig. 25. The region that we desire to count, that is, the 364-kev peak of iodine-131, is accepted in this illustration by the upper and lower PHS settings. How this region may be shifted, expanded, and contracted by the operator is explained later.

Figure 26 shows a block diagram of a scintillation spectrometer. Note that the front end of the spectrometer (shown at left) is the same as the integral-bias counter and has the same function and operation as described before. The lower PHS is the same as the selector (or discriminator) in the integral counter. Furthermore the *E*, or energy, dial (called the "window sill") is the same as the selection level control in Fig. 22. The upper discriminator is set a certain height above the lower discriminator. The outputs of the two discriminators are mixed electronically in such a way that there is an output pulse to the scaler only if a given pulse exceeds the lower discrimination level but not the upper discrimination level.

A clearer explanation of how discrimination is used in pulse-height selection is given pictorially in Fig. 26. Suppose that there are three gamma-ray interactions in the crystal, resulting in energy transfers to the crystal of 120, 360, and 480 kev occurring at times t_1, t_2, and t_3, respectively. (These three pulses are shown as a plot of voltage versus time as they leave the crystal and photomultiplier.) Further amplification is made by the linear amplifier, and these pulses are shaped as seen at the output of the linear amplifier.

Suppose that the lower discriminator is set to a level representing 300 kev and that the upper discriminator is set to a level representing 420 kev. The lower discriminator provides an output for the pulses which exceed its selection level, namely (in this case), the 360-kev (at t_2) and 480-kev (at t_3) pulses (see Fig. 26). Likewise, the upper discriminator will provide an output for any pulse higher than its selection level; in this case it would be the 480-kev pulse at t_3. This is seen on the first line of the waveforms at the lower right. Our discriminator level settings were chosen to accept any pulses in the region 300 to 420 kev so that, with the addition of an anticoincidence (veto) circuit, only the 360-kev pulse at t_2 is allowed to pass to the scaler. The pulse from the upper discriminator at t_3 (from the 480-kev pulse) blocks the corresponding pulse from the lower discriminator and no output is sent to the scaler at t_3.

A good analogy may be drawn between the two discriminator levels and a person sitting in a house looking outside through a window. Below the window, a child throws a series of balls upward and the observer counts only the balls that rise

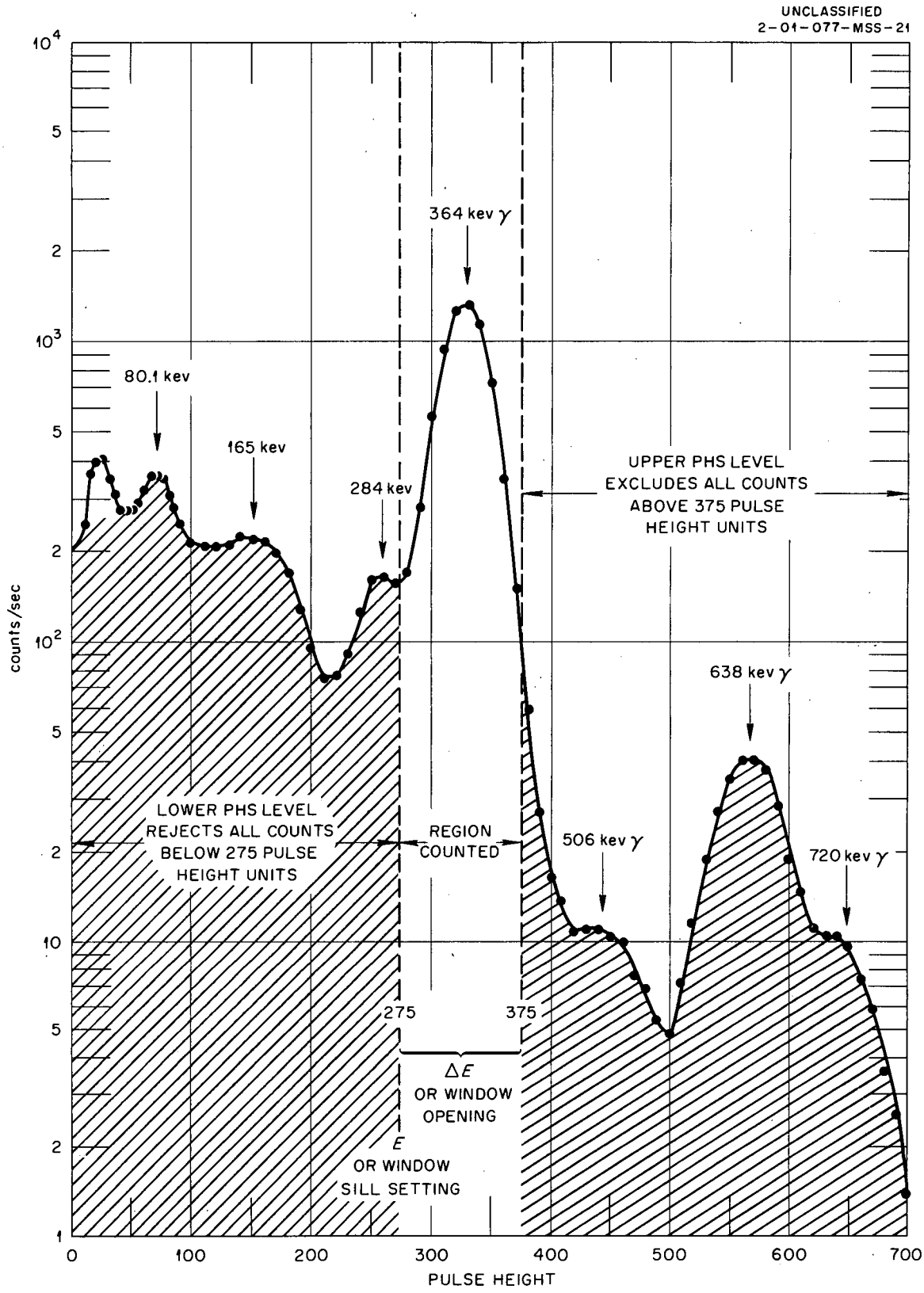


Fig. 25. Iodine-131 Gamma Rays on $1\frac{1}{2} \times 1$ Inch NaI Crystal.

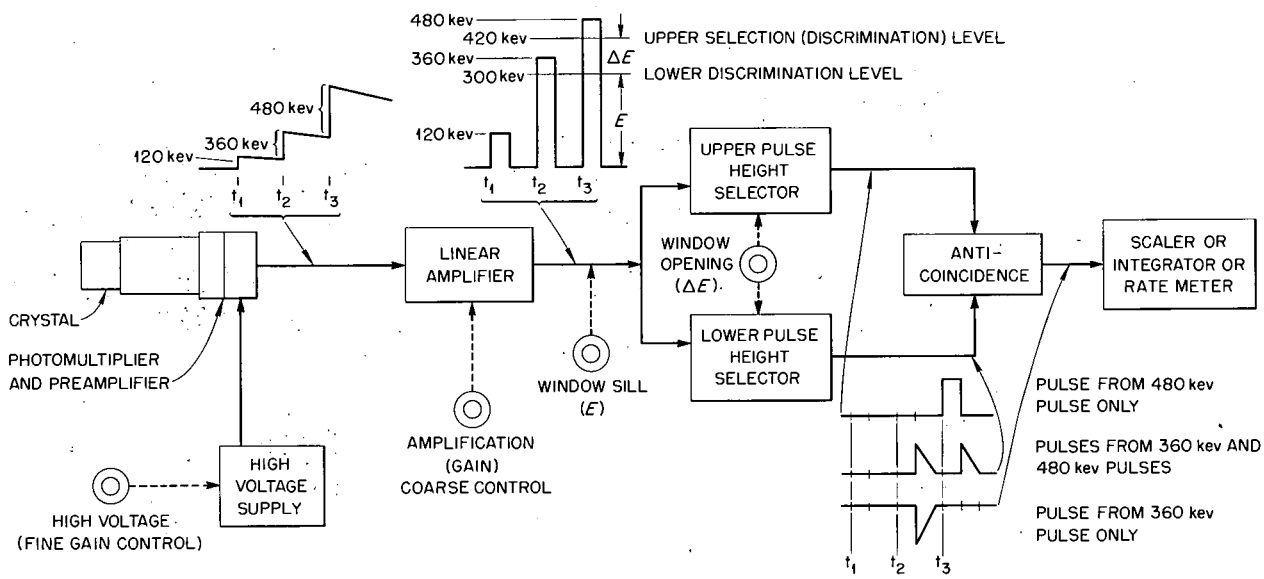


Fig. 26. Scintillation Spectrometer.

higher than the window sill, stop, and start downward before reaching the top of the window. Obviously, those throws reaching a height less than that of the window sill would not be seen. Those going higher than the top of the window would be seen going up and coming down but would not be counted.

The number of throws whose upward flights terminate within the field of view through the window would depend on both the height of the window sill and the width of the window opening. The E dial in Fig. 26 sets the lower discriminator which determines the height of the window sill. The "window," or ΔE dial, on the instrument adjusts the separation between the two discrimination levels.

Note that with the upper discriminator disabled, the spectrometer operates exactly like an integral-bias counter, having only a lower discrimination level (or window sill) and an infinite window opening. The analogy in this case would mean that we would count all the balls thrown to any height above the window sill.

The cost of a complete scintillation spectrometer is only slightly more than a complete high-quality integral counting system, and it has only one more control. It is about twice as expensive as a complete Geiger-tube-substitute counter with its usual (1 × 1 inch) crystal. The spectrometer when properly used can perform any measurement done in diagnostic use of radioisotopes at least *slightly* better than any other instrument and is essential in certain measurements.

Background Reduction. – A scintillation spectrometer can reduce backgrounds considerably (below the levels obtained even with the integral-bias counter) since, even though the gamma rays from a source have some terminal energy, appreciable background extends to very high energies. Much of this high-energy background is rejected by the upper discrimination level. In a typical example the background on a 2 × 2 inch crystal above 60 kev might be 20 counts/sec, above 270 kev, be about 9 counts/sec, and in a region from 270 kev to 400 kev (Fig. 17), be about 2.5 counts/sec.

Adjustment for Proper Use. – Figure 27 shows the front panel of a medical scintillation spectrometer. The window sill or E dial is at the upper right. To its immediate left is the ΔE *or* window opening dial (channel width). Below that is the coarse amplification control (or gain) for the linear amplifier which decreases the amplification in factors of two.

Just left of the meter is the high-voltage control, which can be used as a fine amplification control. The range switch (lower left) and the meter comprise a count-rate meter that can be

Fig. 27. Front Panel of a Scintillation Spectrometer.

used to indicate the counting rate during the alignment of the instrument. Setting up a spectrometer appears perplexing at first but can be done easily with knowledge and practice. In the following example it will be desired to set the center of the window opening at the center of the total absorption peak; this setting will correspond to a window center of approximately 750 pulse-height units, shown in Fig. 28. (For ease of alignment, many persons prefer to provide a 1 to 1 correspondence between kev and pulse-height units on the window sill, or E, dial. Although it is not necessary, we will do this by attempting to set 320-kev gamma rays from chromium-51 equal to 320 pulse-height units.)

1. With a chromium-51 source in front of the crystal, set the ΔE dial to a relatively narrow window opening, say 40 pulse-height units. (Most commercial spectrometers for medical use provide 1000 pulse-height units on the E dial and 100 units on the ΔE dial.) Set the E dial to 300. This places the window sill at 300, but the ΔE dial spans 40 units. The center of the window appears at 320 and the top at 340 units. Obviously the height of the window sill plus half the window opening gives the height of the center of the window.

2. Reduce the high voltage (thus reducing the size of the pulses) until no source counts are obtained. If the high voltage is at a minimum and counts from the source are still obtained, then it is necessary to reduce the gain or amplification of the amplifier.

3. Now increase the high voltage very slowly. The counting rate will be observed to rise, pass over a maximum, fall again, and then rise again, just as if in Fig. 23 we were tracing out the counting rate on the bare-source curve by moving along the curve from right to left (high pulse height to low pulse height).

4. Again reduce the high voltage until no source counts are obtained, then increase it slowly, searching for the first large maximum that occurs. When the setting is found which gives the maximum count rate, the window sill will be set at 300 kev, the center of the window opening at 320 kev, and the top at 340 kev.

5. This window opening is often too narrow to use during routine counting, because it may unnecessarily restrict the counting rate. Actually for routine counting of chromium-51, a window opening extending from 270 kev to 370 kev encompasses the whole absorption peak, giving a good source-to-background ratio, and minimizes the effect of drift changes in the high voltage (pulse size).

In order to accomplish this, with the high voltage set as in step 4, increase the ΔE dial setting to 100 units. The counting rate will go up, but this does not increase the window opening symmetrically about the 320-unit position. The window sill remains at 300, but the center is at 350 (sill

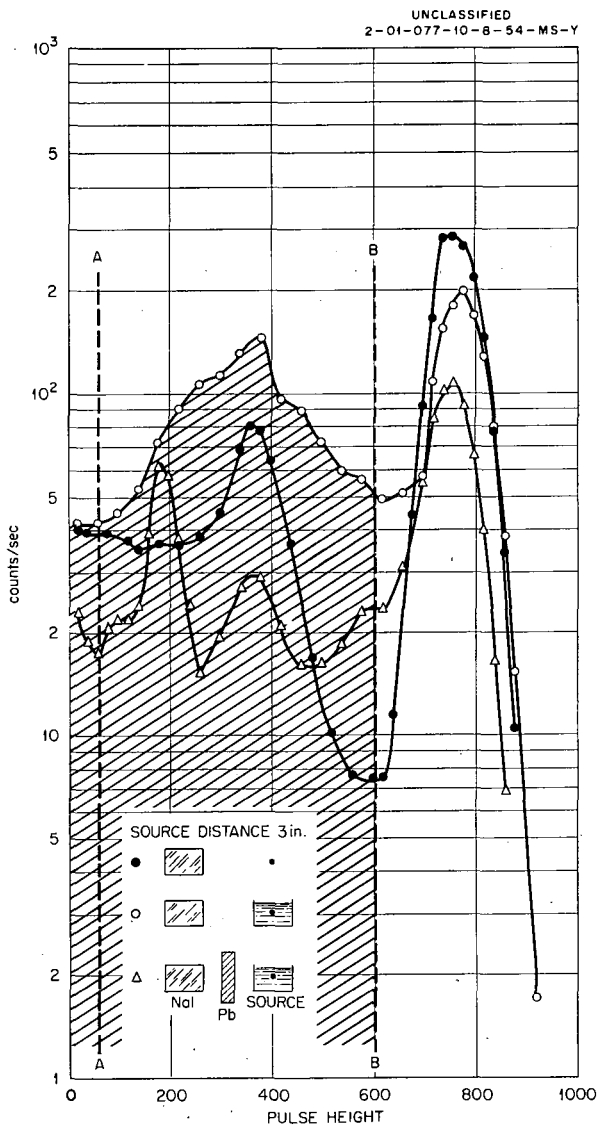


Fig. 28. Pulse-Height Spectrum of Chromium-51 Gamma Rays on 3 × 3 Inch NaI Crystal Under Three Conditions.

plus half of the opening, 300 + 100/2 = 350), and the top at 400.

6. Reduce the E dial to 270, thereby setting the window sill at 270. The center of the window opening is again placed at 320 (270 + 100/2 = 320), and the top at 370 pulse-height units (or kev in this case).

Actually, there is no need to set the pulse height units equal to kev or to 2 kev per unit, but the convenience has been found helpful to many physicians and technicians.

In the following example, we will align the spectrometer using a cesium-137 source (which has a single gamma ray at 661 kev) and then take advantage of the linearity of the instrument to count 364-kev gamma rays from iodine-131 (Figs. 29 and 30).

1. With the cesium-137 source in front of the crystal, set ΔE to 40 and set E to 640, or 660 minus 40/2.

2. Reduce the high voltage (and amplification, if necessary) until no source counts are obtained.

3. Increase the high voltage until source counts are obtained, and then search for the first maximum. This centers the window opening at 660 kev.

4. Remove the cesium-137 source and place an iodine-131 source in front of the crystal.

5. Since the pulse-height scale is linear, set the E dial to 340, or 360 minus 40/2 and search (over small limits) for a maximum if necessary.

6. If it is desired to count more of the peak, then set ΔE to 100 and E to 310. This places the window sill at 310 kev, the center of the window opening at 360, and the top at 410 kev. The window opening encompasses the 364-kev peak of iodine-131 completely for a good source-to-background ratio.

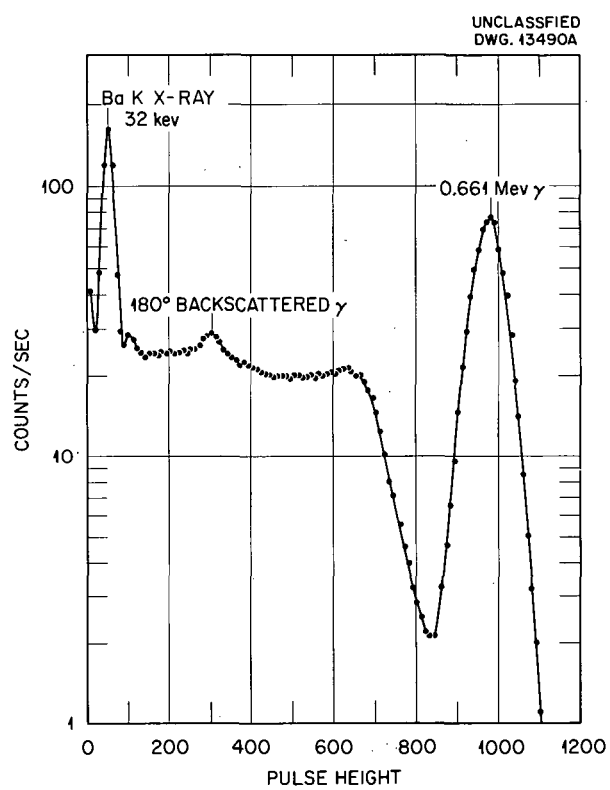


Fig. 29. Cesium-137 Spectrum (1½ × 1 Inch NaI Crystal).

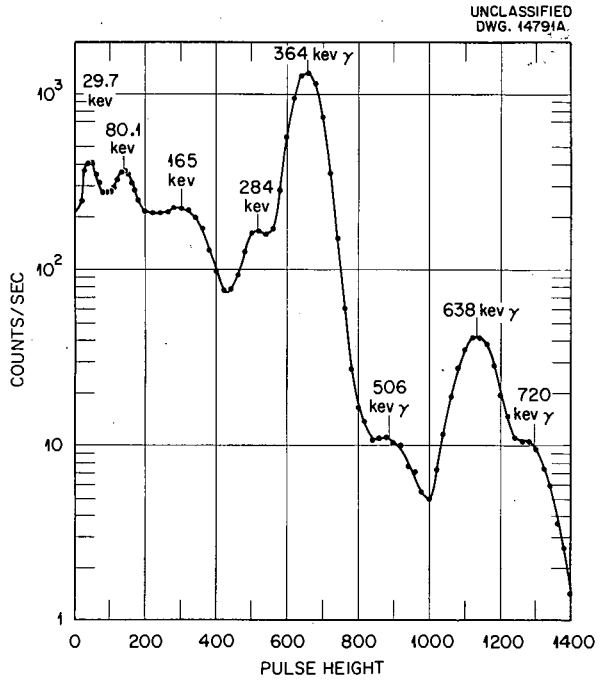


Fig. 30. Iodine-131 Spectrum ($1\frac{1}{2} \times 1$ Inch NaI Crystal).

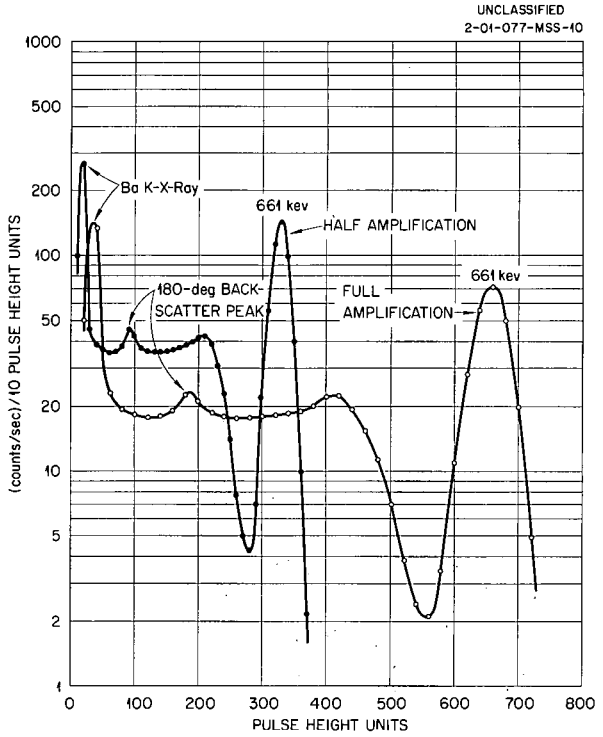


Fig. 31. Count Rate Versus Pulse Height for Cesium-137 Gamma Rays on $1\frac{1}{2} \times 1$ Inch NaI Crystal at Two Gain Settings.

Effect of Amplification Control. – A total absorption peak can be set anywhere on the pulse-height scale; therefore an operator should understand the role of amplification in terms of pulse height and its effect on window opening.

Consider now Fig. 31, which shows a simple cesium-137 spectrum at two different amplification settings, one double the other. Note that the effect of increasing the amplification is to expand all pulses in height by shifting them farther out on the pulse-height axis. This can be done by increasing the amplification, or gain, of the linear amplifier or by increasing the high voltage on the photomultiplier. Pulses from the center of the 661-kev total absorption peak occurring at 330 pulse-height units at one amplification setting occur at 660 pulse-height units when the amplification is doubled. Similarly, there is a factor-of-2 shift in the height of pulses representing the x-ray and backscatter peaks. These curves represent the same source at the same distance from the crystal, and therefore the total counting rate will be the same in both instances.

Note that the effect of increasing the amplification (by increasing the amplifier gain or by increasing the high voltage) is to multiply all pulse heights by a constant factor. This shifts the points on the spectrum to the right.

If we are counting the total absorption curve in the half-amplification case, then the window opening would have to extend from 280 to 370 pulse-height units. This window setting would fully encompass the total absorption peak and give a counting rate of approximately 504 counts/sec. (This number is obtained by adding up the value of each point on the total absorption peak.) If we want to take in the total absorption peak on the full-amplification curve, we must use a window opening extending from 560 to 740 pulse-height units. Now the window opening is double the first one (180 versus 90 units), but the total count rates for both peaks are the same.

At this point, you might be asking: Why are the counting rates in the full-amplification case only half those of the half-amplification curve at corresponding points on the pulse-height scale? The answer lies in the labeling of the count-rate axis, which is "counts per second per 10 pulse-height units." When the half-amplification curve was plotted, window openings of 10 pulse-height units were adjacently spaced along the pulse-height axis. In the full-amplification case, the window openings were again 10 pulse-height units but were

spaced every 20 units along the pulse-height axis. If we had placed 20-pulse-height-unit windows adjacent as we did 10-pulse-height-unit windows in the half-amplification case, we would have obtained a spectrum with the same peak counting rates, but the ordinate would have to have been labeled "counts/sec per 20 pulse-height units," making the total counting rate the same.

This can all be summed up in the following manner: *when you have established a certain window opening and count rate from one absorption peak and you then double the amplification, you must likewise double the window width in order to achieve similar results.*

A practical application of a similar case of this principle might occur as follows: suppose that a spectrometer had been set for making comparative measurements between a standard source and various similar samples. Suppose further that the E dial had been set to 400 and the ΔE to 100. This would have provided a 100-unit window centered at 450 and might have been done in order to place the window squarely on a certain peak. At a later date it was found that in order to center the window opening on the same peak, it would have to be set at 350 PHS. (This could have occurred when someone changed the high-voltage setting.) If the 100-unit window were recentered on the peak, the counting rate of the standard source would be found to be higher than it was before, because the window would now be effectively wider than it was before. In the former case the window opening was 100/450 of the pulse height represented by the center of the window. In the latter case, the window opening was 100/350 of the height of the center of the window. Since the latter fraction is larger, the window in this case would encompass more of the spectrum, giving a higher counting rate for the same standard source. If we wish to avoid resetting the high voltage we could simply reduce the window opening to 78 units, which would make the window encompass the same amount of spectrum as in the former case (100/450 = 78/350).

A Comparison of the Systems

"There is hardly anything in the world that some man cannot make a little worse and sell a little cheaper, and the people who consider price alone are this man's lawful prey." – Attributed to John Ruskin.

A good-quality Geiger-tube-substitute scintillation counter can be used adequately for all sample (or *in vitro*) counting, such as blood volume measurements, with a single labeling isotope. Cardiac output, the Schilling test (Co^{60}-labeled vitamin B_{12}), and similar tests can be done adequately, but with the small crystals usually supplied (1 × 1 inch), sample-to-background counting ratios are not overly high unless good shielding is used. Extreme care must be taken to keep the physical size and location of the source correct. In addition, there is no good indication of malfunction except nonreproducibility of results. The Geiger-tube-substitute scintillation counter must be used extremely carefully for thyroid uptake measurements, is very poor for localizing by scanning, and difficult to use for multiple-tracer work.

By comparison, an integral-bias counter is superior for *in vitro* measurements because of the reduction in background and, when used with thorough understanding (including proper technique and good patient phantoms), can easily provide good thyroid uptake measurements. The elimination of scattered radiation is very useful, but an integral-bias-counter is still inadequate for high-resolution scanning. It can be used with larger crystals (up to 2 × 2 inches) to good advantage for increased sensitivity, because of the background reduction.

Malfunctions with the integral-bias counter are usually detectable, but can sometimes be obscure. However, by plotting an integral spectrum of a known source, an operator can obtain much useful information about the correct functioning of his instrument.

In addition to being superior to the two previously mentioned instruments for the *in vitro* counting, a scintillation spectrometer – when properly used – can give excellent thyroid uptake measurements. It is absolutely necessary for high-resolution scanning and can be used for quick quantitative concentration determinations of the constitution of mixed sources, such as chromium-51 and iodine-131, chromium-51 and iron-59, and sodium-24 and potassium-42. This is accomplished by searching and counting the separate peaks of the two elements in question while blocking off the rest of the spectrum with the proper window width. Incidentally, the integral-bias counter can be used for such measurements but with more difficulty.

Malfunction is moderately easy to detect, but usually the improper use or adjustment of the spectrometer is the cause of the apparent defect.

This can be quickly determined by using the adjustment procedures previously given. Plotting a differential spectrum can be useful in determining the proper operation and perhaps should be done by every spectrometer operator at least once during his familiarization with the device.

Large crystals may be used, facilitating low-level counting and helping in any situation where high ratios of counting rate to background are desired. The large crystals are becoming more widespread in high-resolution scanning, even in relatively simple situations as thyroid scanning, and are essential in such difficult processes as brain-tumor localization.

Actually, spectrometry is necessary to make full use of the virtues of the large crystals. Spectrometry using small crystals does show a dividend, although a much smaller one. In short, if the use of large crystals is desired, the spectrometer method should be used; if the spectrometry method is preferred over other methods, then a large crystal should be provided.