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SCINTILLATION SPECTROSCOPY MEASUREMENTS OF GAMMA-RAY ENERGIES FROM SOURCES OF Y^{88}, Mn^{54}, AND Zn^{65}

R. W. Peelle
T. A. Love

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ABSTRACT

A series of experiments employing NaI(Tl) scintillation spectroscopy techniques was performed to determine the energies of the strong gamma rays in the decays of Y^{88}, Mn^{54}, and Zn^{65}. A variety of calibration sources and counter geometries were used, including some which employed coincidence techniques to observe "double-escape" peaks corresponding to the loss of $2m_ec^2$ from the scintillator. Care was taken to avoid effects from drifts and to correct for nonlinearities of the system. The average gamma-ray energies measured are (1.840 $\pm$ 0.002) Mev and (0.8988 $\pm$ 0.0012) Mev for Y^{88}, (0.8347 $\pm$ 0.0011) Mev for Mn^{54}, and (1.114 $\pm$ 0.004) Mev for Zn^{65}. These values are consistent with averages of published values, but the quoted errors are smaller except in the case of Zn^{65}. When values were deduced for already well-known energies of other gamma-ray transitions, discrepancies between the present measurements and accepted values were consistent with quoted errors.

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INTRODUCTION

In gamma-ray scintillation spectroscopy, reasonably long-lived emitters of strong, isolated gamma rays in the region above 1.4 Mev are required for the study of spectrometer response functions. One isotope frequently considered for this purpose is Y^{88}. The 1.8- and 0.9-Mev gamma ray in the level structure of its daughter Sr^{88} are of nearly equal intensity,[1] though high precision in the measurement of the branching ratio has not been attained. As shown in Table 1, the energies of the Y^{88} gamma rays have been reported by several investigators. They have never been determined by exact methods, however. In fact, only in the recent work of O'Kelley and Johnson does a serious effort seem to have been made to determine the photon energies precisely. This makes the use of these gamma rays for calibration purposes questionable, especially the "1.8-Mev" line, since the quoted measurements for this line are inconsistent with the quoted errors if reasonable errors are assigned where none are given by the investigators.

Since this source was recently used as an energy standard in a lengthy ORNL experiment to determine the spectra of fission-associated radiation,[2] it was decided to measure the Y^{88} gamma-ray energies as well as possible by scintillation spectroscopy techniques. At the same time the energies of two other frequently used sources were checked: the 1.1-Mev gamma ray from the

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1. N. H. Lazar et al., Phys. Rev. 101, 727 (1956); F. M. Tomnovec, Bull. Am. Phys. Soc., Ser. II, Vol. 1, 391 (1956).

2. F. C. Maienschein et al., Proceedings of Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Paper A/CONF. 15/P/670, USA.

Table 1. Published Energies for the Strong Gamma Rays of Y^{88}, Mn^{54}, and Zn^{65}

Nuclide	Authors and Date	Method[a]	Energies and Errors Reported (kev)	
Y^{88}	Downing *et al.*[b] (1941)	sl:pe,ce	(1890±50)	(908±20)
	Scharff-Goldhaber[c] (1941)	Be(γ,n) and proton recoil	(1870±50)[d]	
	Richardson[e] (1941)	Cloud chamber: ce	(1920±30)	(950±50)
	Peacock and Jones[f] (1948)	sl:ce	(1853±37)	(908±18)
	Lazar *et al.*[g] (1956)	scin	(1850±8)	(909±4)
	Tomnovec[h] (1956)	scin	(1850±?)	
	O'Kelly and Johnson[i] (1959)	scin	(1832±6)	(899±4)
	Heath[j]	scin	(1830±?)	(900±?)
	Weighted Average[k] (Using Reasonable Errors Where None Were Given)		(1842±4)	(903±3)
Mn^{54}	Deutsch and Elliott[l] (1944)	sl:ce	(835±15)	
	Stafford and Stein[m] (1953)		(825±20)	
	Maeder *et al.*[n] (1954)	scin	(840±7)	
	Schardt and Dropesky[o] (1956)	(V^{54})scin	(835±9)	
	Van Patter *et al.*[p] (1958)	$Cr^{54}(p,p')Cr^{54*}$ sd, E_p=4.5Mev	(842±6)	
	Weighted Average[k,q]		(839±4)	
Zn^{65}	Jenson *et al.*[r] (1949)	sl:ce	(1118±6)	
	Mann *et al.*[s] (1949)	sl:pe,ce	(1114±5)	(1120±5)
	Hedgran *et al.*[t] (1950)	sd:ce	(1125±6)	
	Waggoner *et al.*[u] (1950)	sl:ce	(1112±7)	
	Good[v] (1951)	scin	(1127±9)	
	Bashilov *et al.*[w]	sd:ce	(1122±5)	
	Johannason[x] (1956)	scin	(1112±3)	
	Weighted Average[k]		(1117±2)	

a. Abbreviations used: scin = scintillation spectrometer; sl = magnetic lens β-spectrograph; sd = double focusing magnetic spectrograph; ce = internal conversion electrons measured; pe = photoelectrons measured (external conversion).

b. J. R. Downing *et al.*, *Phys. Rev.* 60, 470 (1941).

Table 1 (Cont.)

c. G. Scharff-Goldhaber, Phys. Rev. 59, 937A (1941).

d. A recalculation of this value, using more recent values of the ThC" gamma ray and the photoneutron thresholds of the deuteron and Be^9, yields about (1890 ± 21) kev.

e. J. R. Richardson, Phys. Rev. 60, 188 (1941).

f. W. C. Peacock and J. W. Jones, Decay Scheme of Y^{88}, AECD-1812 (CNL-14) (1948).

g. N. H. Lazar et al., Phys. Rev. 101, 727 (1956).

h. F. M. Tomnovec, Bull. Am. Phys. Soc., Series II, Vol. I, 391 (1956).

i. G. D. O'Kelly and N. R. Johnson, Phys. Rev. 114, 279 (1959). The present work was performed before these values were available.

j. R. L. Heath, Scintillation Spectrometry--Gamma-Ray Spectrum Catalogue, IDO-16408, p. 22 (1957).

k. These averages have been obtained using all listed errors as standard errors, and using the formalism of Eqs. 3 and 4. Chi-square tests show the listed values to be internally consistent except for the Y^{88} "1.8-Mev" line, where the probability of greater deviations is $P = 5 \times 10^{-3}$.

l. M. Deutsch and L. G. Elliott, Phys. Rev. 65, 211 (1944).

m. G. H. Stafford and L. H. Stein, Nature 172, 1103 (1953).

n. D. Maeder et al., Physica 20, 521 (1954).

o. A. W. Schardt and B. J. Dropesky, Bull. Am. Phys. Soc., Series II, Vol. 1 162 (1956).

p. D. M. Van Patter et al., Bull. Am. Phys. Soc., Series II, Vol. 3, 38 (1958).

q. A value for Mn^{54} reported by T. Katoh et al., J. Phys. Soc. Japan 13, 1419 (1958), became available too late for consideration in this work.

r. E. N. Jenson et al., Phys. Rev. 75, 458 (1949); 76, 430 (1949).

s. K. C. Mann et al., Phys. Rev. 76, 1719 (1949).

t. A. Hedgran et al., Proc. Phys. Soc. (London) 63A, 960 (1950). (The quoted error is listed as the smallest maximum error which should be considered.)

u. M. A. Waggoner et al., Phys. Rev. 80, 420 (1950).

v. M. L. Good, Phys. Rev. 81, 891 (1951).

w. A. A. Basilov et al., Izvest. Akad. Nauk S.S.S.R., Ser. Fiz. 17, 468 (1953), quoted by F. Ajzenberg-Selove, Nuovo cimento (Suppl.) 4,2 (1956).

x. K. E. Johannason, Arkiv Fysik 10, 247 (1956).

decay of Zn^{65} and the 0.8-Mev gamma ray from Mn^{54}. Previous measurements of these gamma rays, also shown in Table 1, are consistent with each other, but the uncertainties are large.* This is also true of the Y^{88} 0.9-Mev line.

The measurements discussed in this report were performed by comparing the pulse-height distributions induced in NaI(Tl) scintillators by gamma rays of unknown energies with those obtained with gamma rays of known energies. The unknown values were obtained by assuming that the response of the scintillator was linear over the energy region including the unknown and the nearest known energies.

I. EXPERIMENTAL METHOD

General Precautions

Gamma-ray scintillation spectroscopy suffers from inherent uncertainties produced by electronic and phototube gain shifts, pulse-height analyzer zero shifts, scattering effects (not restricted to scintillation spectroscopy), and a broad resolution (full-width at half-maximum) which for the "1.8-Mev" Y^{88} line might typically be 0.1 Mev. The resolution alone seems to prevent an accuracy better than a few kilovolts, especially if the observed full-energy peaks are not precisely symmetrical. In order to minimize such difficulties, the experimental principles listed below were followed with minor exceptions throughout this study.

1. The lowest practical phototube gain was used to diminish the so-called "count-rate drifts," which are largely dependent upon the average phototube anode current.
2. For the same purpose, count rates were usually kept below one or two

*The value for Mn^{54} reported by T. Katoh *et al.*, *J. Phys. Soc. Japan* 13, 1419 (1958), became available too late for consideration in this work. Their value of (837.9 ± 0.3) kev appears to have sufficient precision that the work on Mn^{54} in this paper may be obsolete. Reanalysis of the experiments on Y^{88} and Zn^{65}, using Katoh's value for Mn^{54} as a standard, would have no appreciable effect on the results reported here.

kilocounts per second, and an approximately constant anode current was maintained throughout a given experiment, even when more than one source combination was required.

3. Whenever possible, sources of known energies were measured in the same spectra with sources of unknown energies to eliminate the effect of residual drift.

4. When more than one coincidence circuit or source configuration was used in a single experiment, an odd number of configuration changes was made to allow observation of any drifts. For similar reasons, an attempt was made to allow at least one source to contribute to the spectra during all the runs in a given experiment, even though other sources were alternated.

5. When a pulse-height spectrum for a combination of sources was obtained, separate spectra for the individual sources were also determined so that the effect of each source on the combined spectrum could be subtracted prior to further analysis.

6. A variety of crystal configurations and calibration lines was used to avoid systematic errors.

7. A mercury-switch pulser was used to measure deviations from linearity of the pulse-height analysis system, and corrections were made to the observed positions of gamma-ray peaks to produce an effectively linear response.

8. Estimated standard deviations were recorded at each step of the analysis and combined in a reasonably correct manner. The consistency between these estimated errors and the scatter among the results was used to test the internal consistency of the data. Values and similarly derived errors for known lines were used to check for systematic measurement errors.

One possible precaution was not taken. The sources were not free of scattering material, nor was the environment of the detectors. As a result of this and the wide distribution of source positions employed, the line shapes produced were less symmetrical and systematic than those attainable with great care.[3] Such asymmetries, together with uncertainties in the non-linearity corrections, were the major avoidable sources of error.

Apparatus

Standard pulse-handling equipment was employed. "Stacked" cathode followers mounted near the phototubes drove cables to a DD-2 amplifier,[4] the output of which fed a slightly modified Argonne-type 256-channel analyzer.[5] The conversion gain of the latter unit was altered so that 240 channels corresponded to about 100 volts from the amplifier. Channels above number 200 were seldom used. A mercury-switch pulser incorporating a 0.05%-linearity multiturn potentiometer was used to feed pulses through a small condenser to the grid circuit of the cathode follower. Care was taken to ensure that pulse shapes with the pulser and with the NaI(Tl) were similar. Figure 1 shows the block diagram of the circuity used in the experiments. Only those instruments along the top of the block diagram were used for single-crystal spectroscopy. The entire diagram includes a simple coincidence circuit[6]

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3. R. L. Heath, Scintillation Spectrometry -- Gamma-Ray Spectrum Catalogue, IDO-16408 (1957).

4. E. Fairstein, Rev. Sci. Instr. 27, 475 (1956).

5. R. W. Schumann and J. P. McMahon, Rev. Sci. Instr. 27, 675 (1956).

6. T. A. Love et al., Electronic Instrumentation for a Multiple-Crystal Gamma-Ray Scintillation Spectrometer, ORNL-1929 (1955). (Exact circuit presently used is available as ORNL Dwg. Q-1573.)

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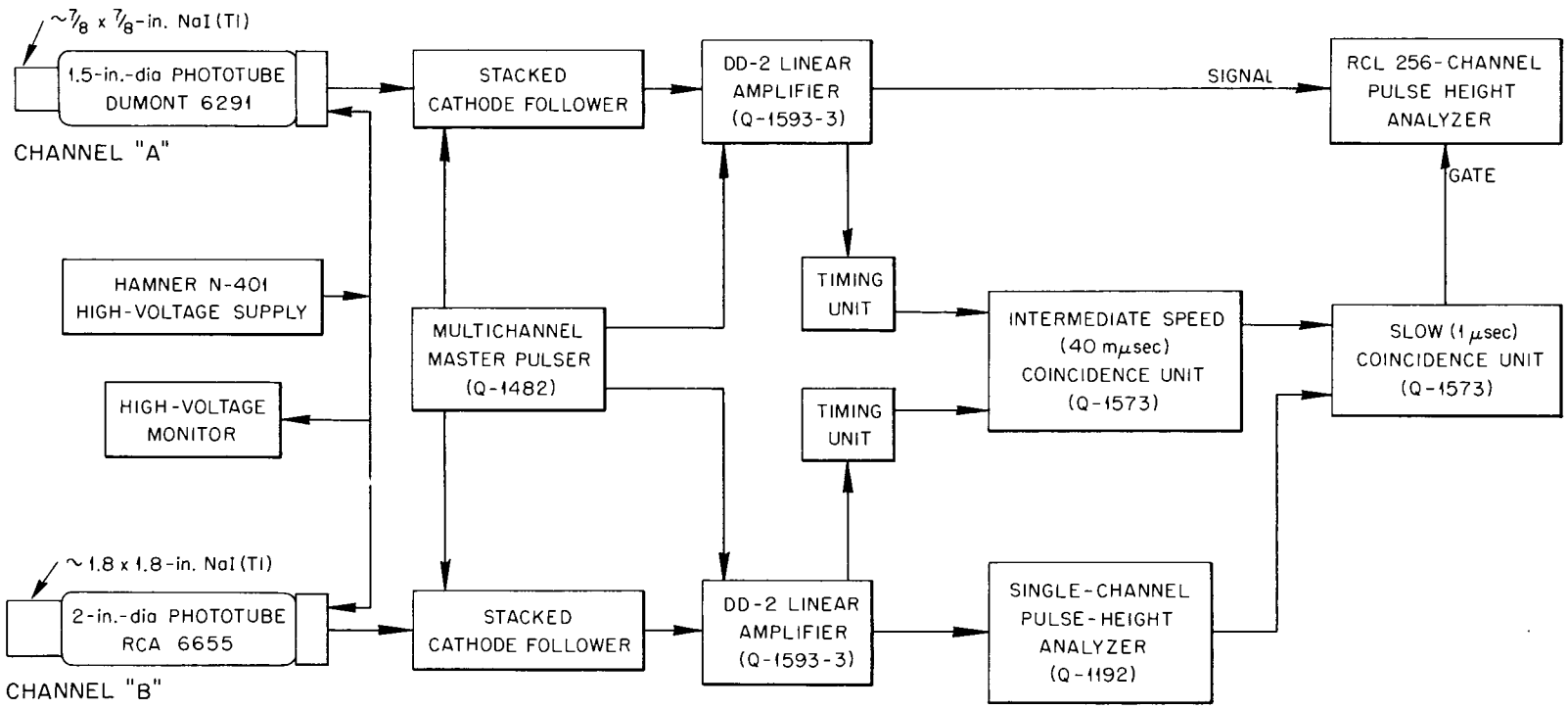

Fig. 1. Block Diagram of Electronic Apparatus Used for Coincidence Measurements. This fast-slow coincidence arrangement is standard except for the timing units which allow a reasonably fast resolving time without the use of fast amplifiers. For "singles" measurements only the instruments shown along the top were used, with other crystals and phototubes substituted for those shown.

(40-millimicrosecond resolving time) used in conjunction with special timing circuits[7] to allow the relative enhancement of the "double-escape" process in the scintillator.

Most of the sources were encapsuled in quartz ampoules within soldered 1-in.-long by 1/4-in.-OD brass cylinders, though some were in thinner or thicker containers. Table 2 lists the calibration sources used, the assumed or assigned errors in their energies, and the references from which the values were obtained. With the exception of Na^{24} and La^{140}, the errors are sufficiently small that their values did not affect the analysis.

Three different NaI(Tl) crystal and photomultiplier arrangements were used as follows:

1. A 1.5-in.-dia by 2-in.-long crystal mounted on a 2-in. RCA-6655 phototube. This was the largest crystal which would give a reasonable double-escape peak from the 2.75-Mev gamma rays of Na^{24}. (This peak was eventually ignored in the analysis, however; see p. 18 .)
2. A 3 by 3 in. cylindrical crystal mounted on a 3-in. Dumont-6363 phototube. This crystal size was chosen for high efficiency and peak-to-total ratio in the energy range of interest.
3. An approximately 7/8 by 7/8 in. "A" crystal with four flat faces, used in conjunction with an approximately 1.8 by 1.8 in. "B" crystal as shown on p. 10. This combination was used to isolate the peak in the spectrum of the smaller crystal which

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7. R. W. Peelle and T. A. Love, Applied Nuclear Phys. Div. Ann. Prog. Rep., Sept. 1, 1957, ORNL-2389, p. 249.

Table 2. Energies of Calibration Sources[a]

Calibration Number	Source	Energy (kev)[b]	References
1	m_e (annihilation radiation)	510.976 ± 0.007	Dumond and Cohen[c]
2	Na^{22}	1275.0 ± 0.5	Ajzenberg and Lauritsen[d]
3	Na^{24}	1368.0 ± 1.0	Hedgran and Lind[e]
4	Na^{24}	2753.5 ± 1.0	Hedgran and Lind[e]
5	$(Na^{24} - 2m_e)$	1732.5 ± 1.0	Hedgran and Lind[e]
6	Bi^{207}	569.6 ± 0.1	Way *et al.*[f]
7	Bi^{207}	1063.7 ± 0.3	Way *et al.*[f]
8	Cs^{137}	661.6 ± 0.2	Way *et al.*[g]

a. These source energies and errors were used in the analysis.

b. The values given have been averaged from those in the referenced papers and compilations. The errors quoted are estimated standard errors based on errors given in these papers and the scatter between the values quoted.

c. J. W. M. Dumond and E. R. Cohen, *Handbook of Physics*, edited by E. V. Condon and H. Odishaw, pp. 7-170, McGraw-Hill, New York, 1958.

d. F. Ajzenberg and T. Lauritsen, *Revs. Mod. Phys.* 27, 77, esp. p. 155 (1955). A larger uncertainty should have been assigned to the N^{22} energy, based on scatter between the various observations; however, this oversight is quite unimportant because this source was infrequently used.

e. A. Hedgran and D. Lind, *Arkiv Fysik* 5, 177 (1952).

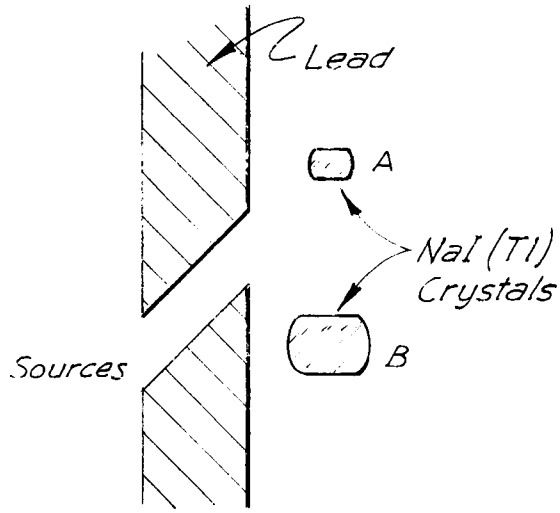
f. K. Way *et al.*, *Nuclear Data Sheets*, NRC 58-2-66, National Academy of Sciences, National Research Council.

g. K. Way *et al.*, *op.cit*, Sheet NRC 58-4-31.

corresponds to the escape of an annihilation radiation from that crystal. The apparatus connected with the larger crystal was set to accept only those pulses corresponding to the energy range between 0.41 and 0.61 Mev.

Description of Experiments

In all, 13 independent experiments were performed. Descriptions of the experiments are given in Table 3. The primary purpose indicated in each case is that for which the experiment was designed, though each set of data was analyzed for all usable information.



II. ANALYSIS PROCEDURES

Subtraction of Interfering Pulse-Height Distributions

Whenever the differential pulse-height spectrum corresponding to one gamma ray was not flat in the region of the full-energy peak of another, simultaneously measured gamma ray, a subtraction was performed using a spectrum for the interfering gamma ray measured with the source in the same position it occupied during the combined run. Figure 2 gives three examples, one for each crystal configuration. This process was seldom required with the 3 by 3 in. crystal.

Table 3. Description of Experiments

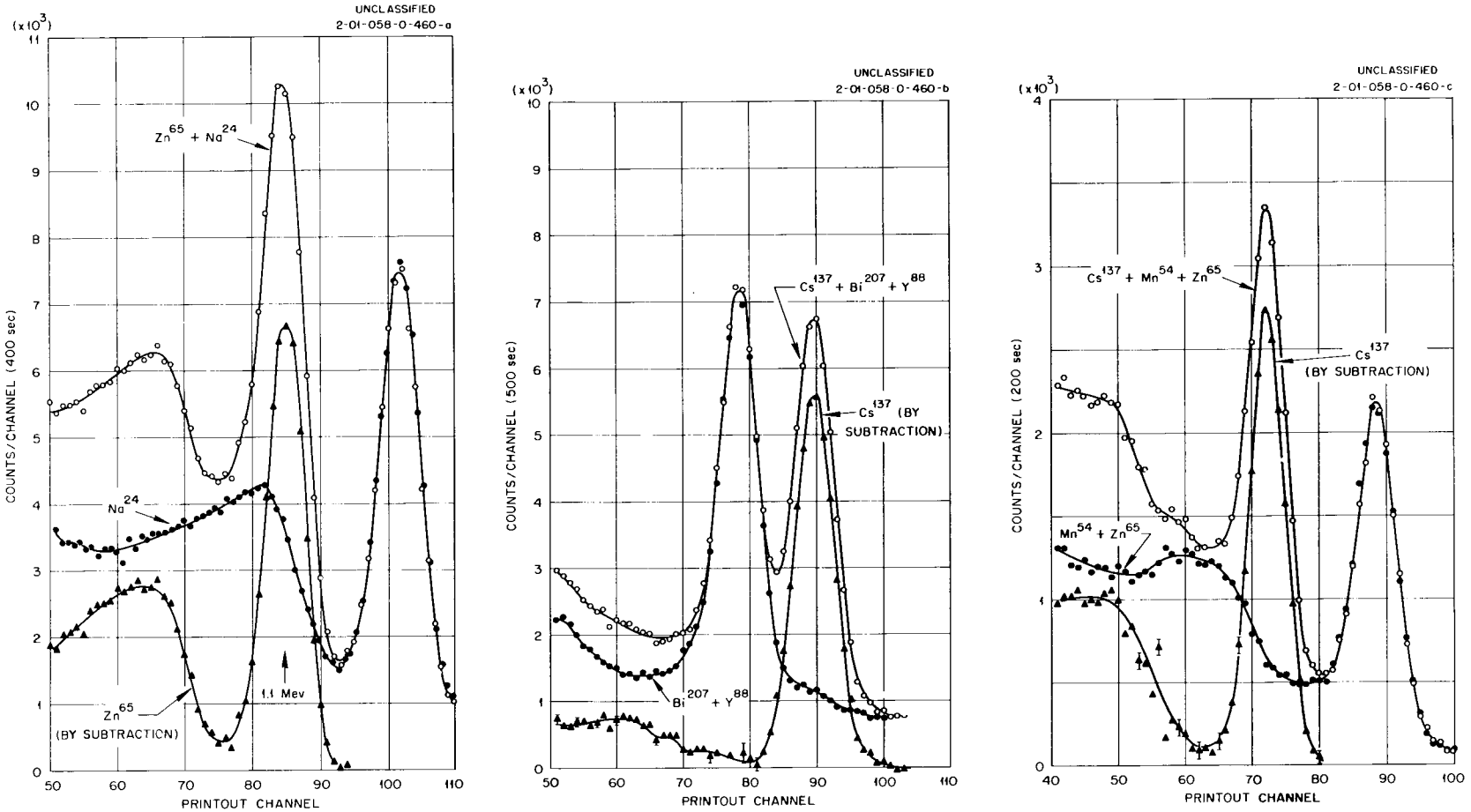
Exp. No.	Crystal Configuration[a]	Sources Utilized	Cycles of Change[b]	Approximate Gain (kev/ch)	Gamma-Ray Line for Which Measurement Was Primarily Designed[c]
1	2	Y^{88} vs Na^{24}	2.5	15	Y^{88} "sum" peak[d]
2	2	(Y^{88}+Zn^{65}) vs (Na^{24}+Zn^{65})	2.5	15	Y^{88} "sum" peak
3	2	(Y^{88}+Bi^{207}) vs (Y^{88}+Ca^{137})	2.5	11	0.9 Mev (Y^{88})
4	1	(Y^{88}+Bi^{207}) vs Na^{24}	2.5	13	1.8 and 0.9 Mev (Y^{88})
5	1	(Y^{88}+Zn^{65}) vs (Na^{24}+Zn^{65})	2.5	15	1.8 Mev (Y^{88})
6	3	Y^{88}+Na^{24}+Cs^{137}, singles vs coincidence	1.5	18	1.8 Mev - $2m_e$(Y^{88})
7	3	Y^{88}+Na^{24}+Cs^{137}	1.5	14	1.8 Mev - $2m_e$(Y^{88})
8	2	(Zn^{65}+Mn^{54}) vs (Na^{22}+Bi^{207}+Mn^{54})	3	8	1.1 Mev (Zn^{65})
9	2	Bi^{207}+Mn^{54}+Cs^{137}	2	6	0.8 Mev (Mn^{54})
10	2	(La^{140}+Na^{24}) vs (Bi^{207}+Na^{24})	2	12	Bi^{207} "sum" peak
11	3	(Y^{88}+Na^{24}), singles vs coincidence	2.5	17	1.8 Mev (Y^{88})
12	3	Y^{88} coincidence vs (Cs^{137}+Zn^{65}+Mn^{54}) singles	2	11	1.8 Mev - $2m_e$(Y^{88})
13	2	(Y^{88}+Bi^{207}+Cs^{137}) vs (Mn^{54}+Bi^{207}+Cs^{137})	1.5	9	0.9 Mev (Y^{88}) and 0.8 Mev (Mn^{54})

a. See p. 8 for definition of the crystal configuration numbers.

b. When an experiment consisted of a comparison between two coincidence circuit and/or source arrangements, the number of cycles of such a change is entered here. When no such comparison is indicated, this number just shows the number of repeated runs in the experiment.

c. In each case it was planned to calibrate against the nearest well-known lines. For crystal configurations 1 and 3, especially for configuration 3, use was made of the 1.732-Mev Na^{24} peak corresponding to the "double escape" from the crystal of all annihilation radiation.

d. "Sum" peaks are produced by simultaneous detection of coincident cascade gamma rays. These peaks were of importance for a study of nonproportionality of response (see R. Peelle and T. A. Love, Observation of Nonproportionality of Response for a NaI(Tl) Scintillation Crystal, ORNL-2801 (1959)).



a. Separation of Zn^{65} 1.1-Mev line from combination of Zn^{65} and Na^{24} (Exp. 5).

b. Separation of Cs^{137} 0.66-Mev line from combination of Cs^{137}, Bi^{207}, and Y^{88} (Exp. 13).

c. Separation of Cs^{137} 0.66-Mev line from combination of Cs^{137}, Mn^{54}, and Zn^{65} (Exp. 12).

Fig. 2. Examples of Subtracting Interfering Pulse-Height Distributions from Experimental Pulse-Height Spectra. Note how apparent position of the desired peak is slightly shifted by the correction. See Table 3 for descriptions of experiments.

Determination of Channel Number Corresponding to Each Peak

Figure 3 shows three typical full-energy peaks as they were plotted for determination of the channel number to be associated with the peak. All peaks were originally plotted on a linear scale of about four channels per inch. Straight lines were drawn on the sides of the peaks as shown in Fig. 3, and the midpoint of the peak was determined at two or more count-rate levels. If the two lines representing the sides of the peaks had exactly opposite slopes, indicating symmetry of the peak, the standard error was estimated from the scatter of the experimental points about the lines drawn on the sides of the peak. When the peak was asymmetrical, the estimated standard error was correspondingly increased and the peak position was taken as the average of the channel numbers at which the count-rate attained about two-thirds its maximum value.

Averaging of Identical Runs

Table 4 shows the experimental results tabulated from Exp. 5, a case exhibiting more than the typical amount of drift. Only the results from the middle three spectral determinations (1.5 cycles) were used in the analysis, since drifts may be indicated by the differences between the results tabulated from "spectrum 1" and those from the remaining spectra. The averages were taken in a rather direct manner, and the combined standard errors reflect a judgment concerning how much of each estimated error is systematically common to all the spectral results which were averaged.

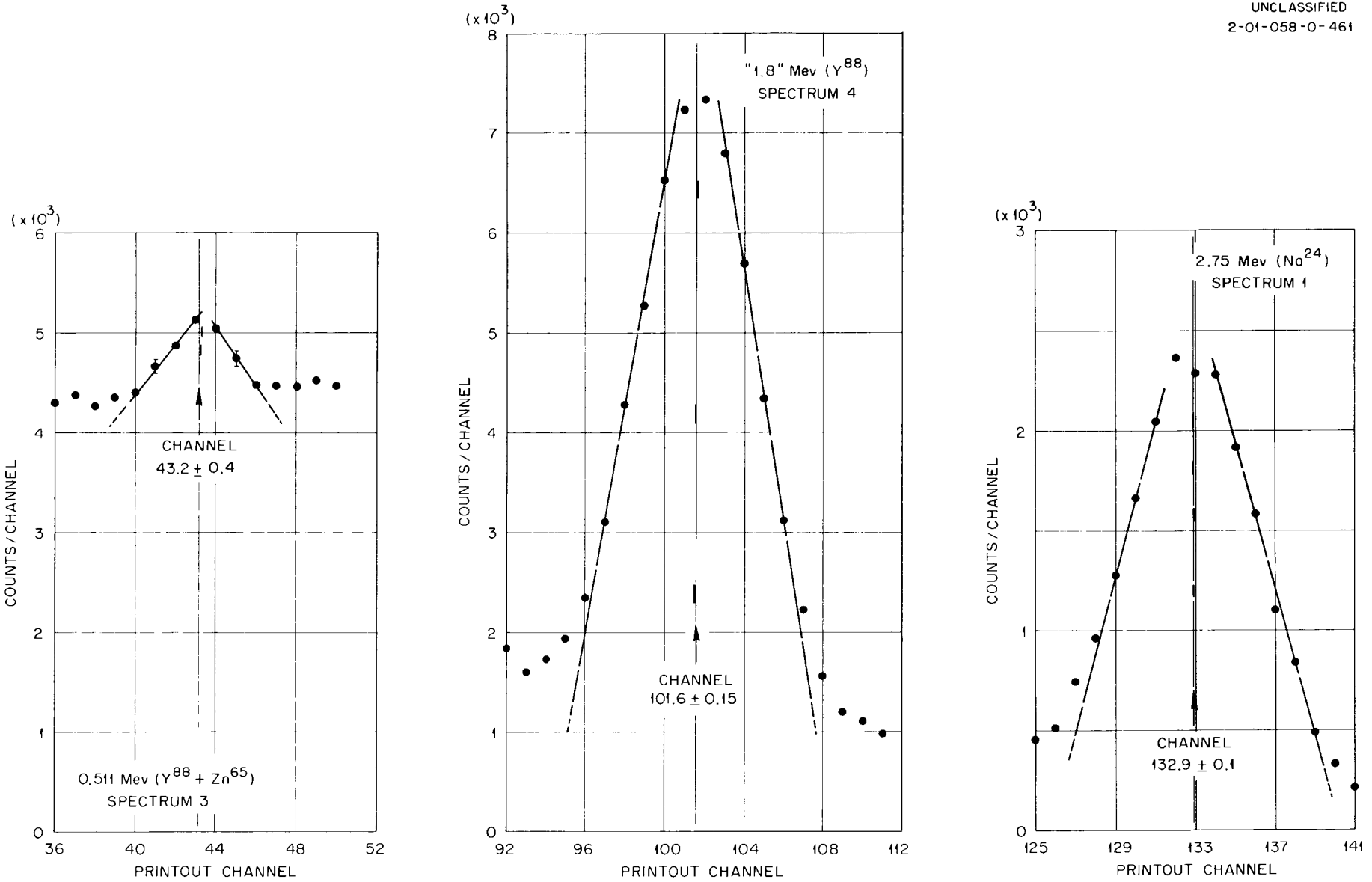


Fig. 3. Typical Plots Used to Determine the Positions of Photopeaks. The plotted peaks are part of the data from Exp. 5, on which Table 4 is based.

Table 4. Channel Numbers for Peak Positions Observed in Experiment 5

	Channel Number[a]						
	0.511-Mev Peak	"0.9-Mev" Peak	"1.1-Mev" Zn^{65} Peak	1.37-Mev Na^{24} Peak	1.73-Mev Na^{24} Peak	"1.8-Mev" Y^{88} Peak	2.75-Mev Na^{24} Peak
Spectrum 1 (Y^{88}+Zn^{65})	43.9±0.3	70.4±0.15	85.2±0.1			132.9±0.1	
Spectrum 2 (Na^{24}+Zn^{65})	43.1±0.2		84.8±0.1	101.7±0.2	125.2±0.3		193.5±0.4
Spectrum 3 (Y^{88}+Zn^{65})	43.2±0.4	70.1±0.15	84.9±0.1			132.6±0.15	
Spectrum 4 (Na^{24}+Zn^{65})	43.1±0.2		85.0±0.1	101.6±0.15	125.2±0.3		193.7±0.3
Spectrum 5 (Y^{88}+Zn^{65}	43.2±0.2	70.0±0.15	84.8±0.1			132.4±0.15	
Average Channel Number (Spectra 2, 3, 4)	43.15±0.2	70.1±0.15	84.9±0.1	101.65±0.15	125.2±0.2	132.6±0.15	193.6±0.3
Nonlinearity Correction[b]	0.15±0.2	-0.9±0.2	-0.4±0.15	-0.4±0.15	-0.1±0.2	-0.1±0.1	0.4±0.2
Adjusted Average Values	43.3±0.3	69.2±0.25	84.5±0.17	101.25±0.2	125.1±0.3	132.5±0.17	194.0±0.35

a. Channel numbers and errors taken from graphs such as those in Fig. 3.

b. Obtained from the graph reproduced in Fig. 4.

Nonlinearity Corrections

Table 4 also shows the corrections made for nonlinearities observed with pulser data such as that exhibited in Fig. 4. The correction applied to each peak channel number was the difference observed at the listed channel number between the corresponding pulser point and the arbitrary straight line drawn near the pulser points in Fig. 4. This method is valid because the zero pulse-height intercept on the energy scale is assigned no significance. The estimated standard error assigned to each nonlinearity correction is based on the ± 0.1-channel uncertainty in each pulser point and the difficulty in interpolating from the linearity curve a correction for the channel in which the gamma-ray peak is located. The final corrected value and its error shown in Table 4 are obtained by straightforward combination, assuming randomness of errors.

Systematic Errors

At least two important sources of systematic error could not definitely be eliminated by the above analysis method: (1) residual nonlinearities, and (2) systematic line-shape difficulties.

Residual nonlinearities were apparent in some experiments in the positions of X-ray lines and any lines which appeared above channel 200 of the pulse-height analyzer. Such peak positions, even after correction for nonlinearities observed using the precision pulser, frequently did not fall within error of the channel position expected on the basis of other calibration data. Such lines fell in regions where the nonlinearity corrections are not considered reliable. It is believed that this effect is caused by the slight differences

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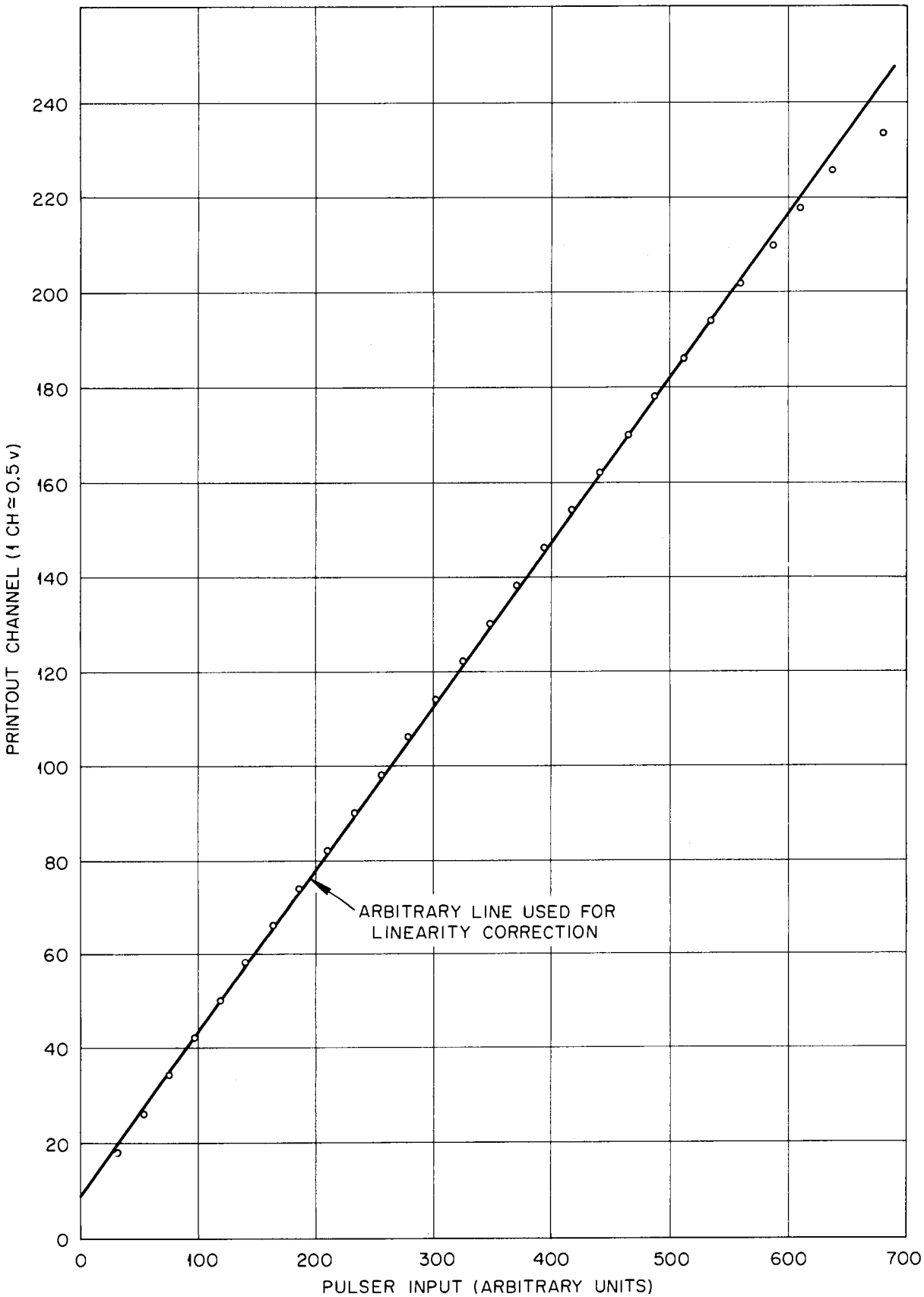

Fig. 4. Typical Pulser Response Curve Used to Generate Nonlinearity Corrections.

in pulse shape between the pulses from the NaI-phototube combination and from the pulser, and presumably by the anticipated instability of any nonlinearities present in a system designed to be linear. These effects are known to be most serious near either extreme of the scale. Therefore, essentially all the values reported from this experiment were obtained using the central range of the analyzer between about channel 40 and about channel 170. The degree of consistency of the results discussed in a later section tends to confirm the nonlinearity corrections within this central region.

Figure 5 illustrates the effect of the nonlinearity on the data from Exp. 5. Weighted least-squares fits were made to the data of Table 4 before and after application of the nonlinearity corrections. The figure shows that prior to correction the calibration data are quite inconsistent with a straight line, while after correction there is no significant departure from linearity.

Figure 6 shows the two cases in which systematic line-shape difficulties are thought to have influenced the position of peaks in the pulse-height spectra. Figure 6a shows the distribution obtained with the 1.5-in.-dia by 2-in.-long crystal (Conf. 1) for the double-escape peak from the 2.75-Mev gamma ray in the decay of Na^{24}. The peak is somewhat asymmetric, and tests indicate that calibrations are somewhat less internally consistent when data from this peak is included. Therefore, it was not used in interpolating the energies of unknown lines. Figure 6b shows the "doubles" coincidence spectrum obtained using a Na^{24} source with the two-crystal configuration (Conf. 3). The double-escape peak is satisfactory, but the single-escape

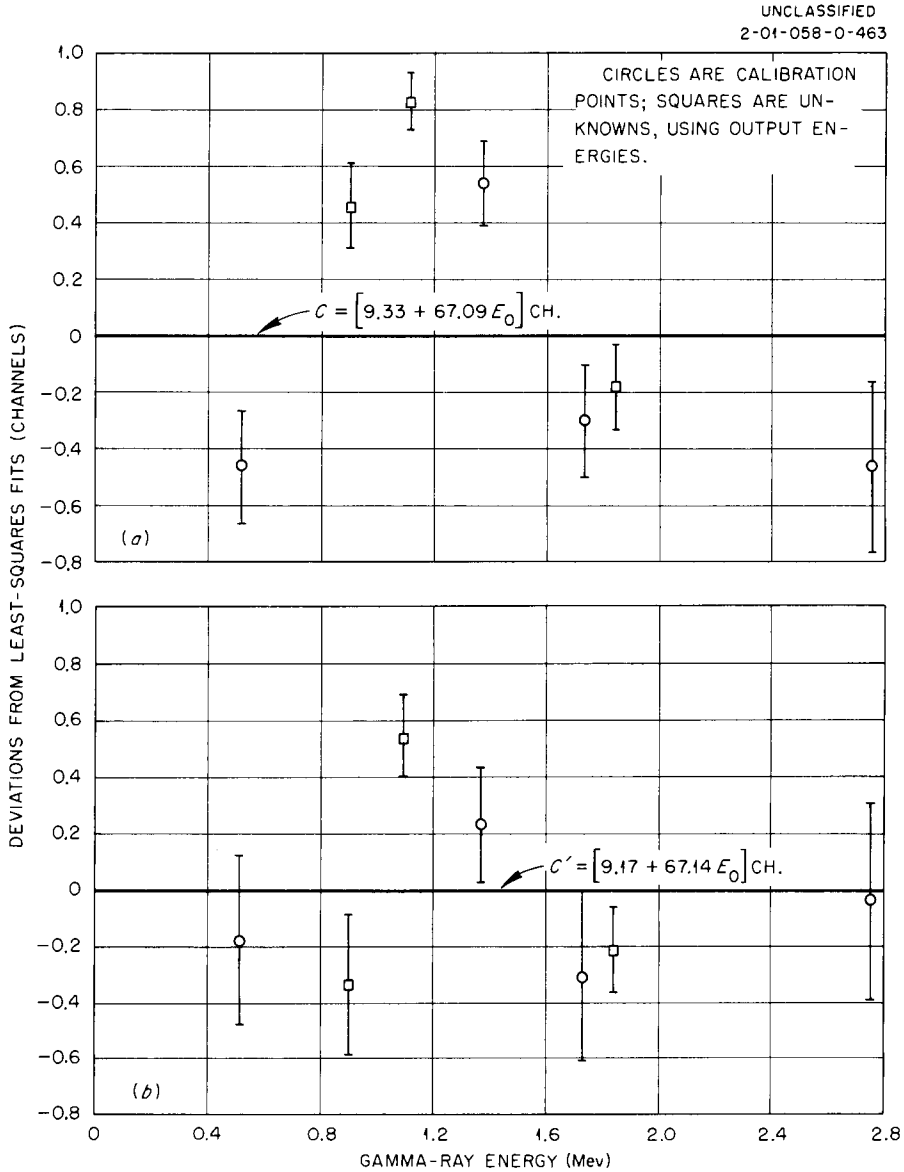

Fig. 5. Demonstration of Linearity of the Pulse Height vs Energy Relation Before (*a*) and After (*b*) Linearity Corrections Based on Fig. 4. These data are from Exp. 5 and are tabulated in Table 4. The ordinates represent deviations between observed peak positions and the best (least-squares) fit to the four calibration points. Points corresponding to three of the unknowns are also plotted, assuming the final energy values from this paper in calculating the plotted deviations. Calibration data using the 1.73-Mev "double-escape" peak of Na^{24} has been included here, though it was not used in the analysis for best output values. Note that for the unlinearized data (*a*) the calibration points are inconsistent with the best fit, the probability of greater deviations with the quoted errors being less than 5×10^{-4}. When the linearized data (*b*) are compared to the least-squares line for the calibration points, they are consistent with a straight line, the probability of greater deviations being 0.15. The circled calibration points superficially appear to be more consistent than this because only two degrees of freedom are available for the consistency test. Energy output values for the unknowns based on this least-squares analysis gives results within less than one-half the standard error of the values quoted in Table 5 on the basis of interpolation between the closest calibration points.

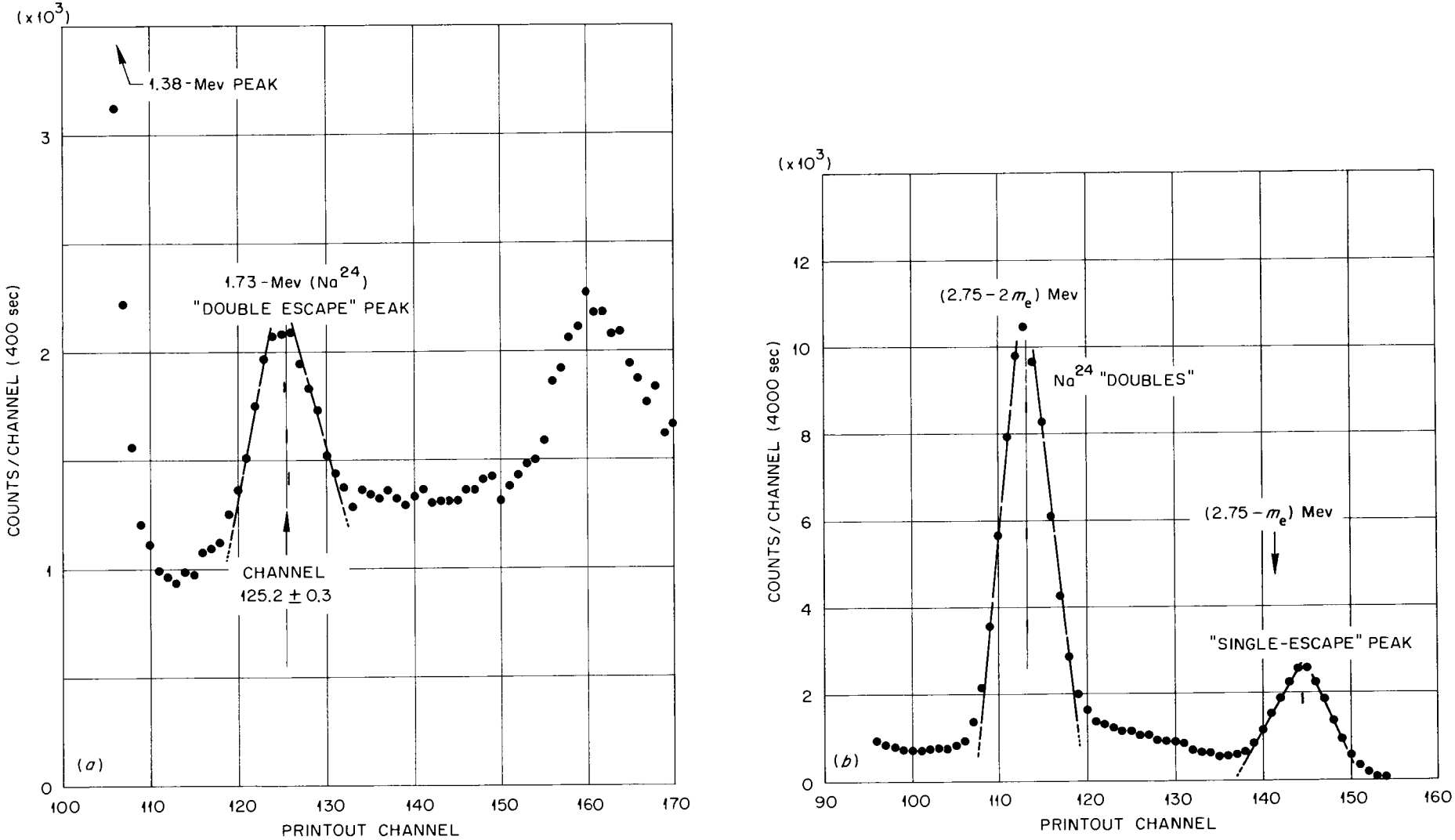

Fig. 6. Line Shape Difficulties. (*a*) The "double-escape" peak for the 2.75-Mev gamma ray in the decay of Na^{24} as observed with a 1.5-in.-dia by 2-in.-long NaI(Tl) crystal during Exp. 5. (*b*) "Single-" and "double-escape" peaks from the same gamma ray as observed in Exp. 11 by the two-fold coincidence spectrometer.

peak is incorrectly placed by three channels. This peak contains enough pulses corresponding to Compton scattering events at nearly 90 deg to shift the peak from the position expected on the basis of escape of a single annihilation photon. These single-escape peaks were not used in any way.

The assumption was made that no other significant systematic errors existed. The only available test was the degree of accuracy obtained in the measurement of known gamma-ray energies.

Interpolation Method for Output Energies and Errors

This section describes the manner in which each set of data such as that exhibited within Table 4 was used to determine the energies which correspond to each of the channel numbers in which peaks from unknown gamma rays occurred.

Since some residual nonlinearity may have been present after correction, it was not considered worth while to perform a least-squares analysis on each set of calibration data to obtain the "best" output values. In principle, such an analysis including terms of a higher degree than linear could have yielded better results than did the simpler method used, but it is estimated that such an analysis would have reduced output error estimates only 10 to 15%, with corresponding minute changes in the output energies.

The output energy estimates were based on a linear interpolation between the two nearest calibration points, except in a few cases for which two closely spaced calibration points were averaged. Only a few short-range extrapolations were needed and one long-range extrapolation was used. In every case errors were propagated assuming normal error distributions with

the estimated standard deviations. Thus if

$(E_n \pm \epsilon_n) \equiv$ the output energy value and its estimated standard error for an unknown gamma ray in Exp. n (kev),

$(E_1 \pm \epsilon_1), (E_2 \pm \epsilon_2) \equiv$ the two calibration energies and their standard deviations taken from Table 2 (kev),

$(C_j \pm \gamma_j) \equiv$ the channel number and error associated with the pulse-height measurement of E_j, in experiment n $\left[E_j = E_1, E_2, E_n\right]$,

$g \equiv$ the conversion gain ($\text{Mev}\cdot\text{ch}^{-1}$) between the calibration points

$$\equiv \frac{(E_2 - E_1)}{(C_2 - C_1)}$$

and if

$$f_1 \equiv \frac{(C_n - C_1)}{(C_2 - C_1)} \quad \text{and } f_2 = 1 - f_1 = \frac{(C_2 - C_n)}{(C_2 - C_1)}$$

are the interpolation fractions, then

$$E_n = E_1 + g(C_n - C_1) = f_2 E_1 + f_1 E_2 \tag{1}$$

and

$$\epsilon_n^2 = f_2^2\, \epsilon_1^2 + f_1^2\, \epsilon_2^2 + g^2 \left[\gamma_n^2 + f_2^2\, \gamma_1^2 + f_1^2\, \gamma_2^2\right] \tag{2}$$

Usually the values of f_1 and the errors in the input energies were sufficiently small that γ_n and γ_1 were the main contributions to the final propagated errors.

Combination of Results from Individual Experiments

Final results for each of the energies studied were weighted averages of the values obtained from the several experiments, where the weights were taken as inversely proportional to the estimated variance of the individual values. Suppose that

$(E_n + \epsilon_n)$ = energy and error obtained from Eqs. 1 and 2 for the nth measurement of a gamma ray under consideration, and

$W_n = 1/\epsilon_n^2$ = weight assigned to E_n in obtaining

$(\bar{E} \pm \sigma(\bar{E}))$ = the output value and error of an unknown gamma ray.

The following relations were utilized:

$$\bar{E} = \frac{\Sigma_n W_n E_n}{\Sigma_n W_n}, \qquad n = 1,2,\ldots, N. \tag{3}$$

and

$$\sigma^2(\bar{E}) = \frac{\Sigma_n W_n \epsilon_n^2}{(\Sigma_n W_n)^2} = \frac{1}{\Sigma_n W_n} \tag{4}$$

"Chi-square" tests were performed to see if the scatter among the experimental E_n values was consistent with the quoted random errors. In the above notation,

$$\chi_\nu^2 = \Sigma_n W_n (E_n - \bar{E})^2 \tag{5}$$

where ν is the number of degrees of freedom, taken as N - 1. From χ_ν^2 one obtains $P(\chi^2, \nu)$, which is the probability that another set of experimental values would have produced larger values of χ^2 if the quoted ϵ_n values are the correct standard deviations of normal error distributions.

This analysis assumed that the errors assigned to the results of each measurement are independent. The estimates of error (ϵ_n) met the criterion of independence except in the following rather minor respects:

1. Estimated errors in the Na^{24} energies made small contributions to more than one of the experimental values.
2. Errors in obtaining and plotting pulser linearity curves such as the curve in Fig. 4 were common to more than one value, though the major error in the nonlinearity correction was in reading the correction from such a graph, done independently for each case.

Systematic errors common to the entire set of values are unlikely at least in the case of Y^{88}, since so many experimental configurations were employed. The consistency test described above does not provide any check for such errors.

III. RESULTS

Table 5a gives a complete summary of the results of all the individual experiments, including the errors estimated for each of the unknown energies studied. Similarly obtained estimates for some known gamma-ray energies in terms of the other available standards are given in Table 5b. The standard energies used for the interpolation are shown. By the nature of the experiments, in which calibration energies were chosen to reduce systematic errors in unknowns, systematic errors should be most evident for the long interpolations required for the auxiliary estimates of known energies. Random error estimates were made in the same manner for all cases, using Eq. 2.

Table 5. Summary of Gamma-Ray Energies Determined from Various Experiments[a]

Source	Experiment Number[a]	Standards Used[b]	Measured Energy[c] (kev)
	Unknown Transition Energies		
"0.84-Mev" Mn^{54}	8	1,7	837.0±2.9
	9	6,8;7	834.6±1.6
	12	(1114±3)kev,8	834.5±4.2
	13	6,8;7	833.8±2.0
"1.1-Mev" Zn^{65}	2	1,3	1104.6±4.3
	5	1,3	1120.3±3.7
	8	7,2	1114.3±3.0
"0.9-Mev" Y^{88}	1	1,3	897.5±4.5
	2	1,3	896.8±4.2
	3	6,8;7	896.3±2.6
	4	6,7	899.4±3.9
	5	1,3	894.0±4.7
	6	8;3,5	906.2±7.7
	7	8,3	899.9±5.2
	11	1,3	902.3±4.0
	13	6,8;7	900.4±2.1
"1.8-Mev" Y^{88}	1	3,4	1848.6±3.9
	2	3,4	1846.5±3.8
	4	3,4	1831.0±4.1
	5	3,4	1834.8±3.6
	6	8;3,5 ($+2m_e$)	1848.4±6.5
	7	8,3 ($+2m_e$)	1837.3±5.2
		5,4	1841.0±6.9
	11	1,3 ($+2m_e$)	1847.0±4.5
		5,4	1842.5±4.5

Table 5. (cont.)

Source	Experiment Number[a]	Standards Used[b]	Measured Energy[c] (kev)
	12	(1114+3)kev,8 (+$2m_e$)	1832.6±4.2
	13	6,8;7	1832.8±6.3
	Known Transition Energies		
0.66-Mev Cs^{137}	3	6,7	666.3±3.7
	9	6,7	662.2±1.8
	13	6,7	666.7±2.2
1.06-Mev Bi^{207}	4	6,3	1070.0±6.0
	8	1,2	1066.6±3.0
	10	6,3	1066.5±3.2
1.37-Mev Na^{24}	1	1,4	1372.4±4.5
	2	1,4	1372.0±4.5
	4	7,4	1364.6±5.6
	5	1,4	1373.5±4.6
	6	8,5	1364.1±7.5
	7	8,4	1359.4±5.7
	10	7,9	1368.5±3.3
	11	1,4	1371.6±4.5
1.73-Mev Na^{24}	4	3,4	1717.8±4.8
	5	3,4	1724.3±5.3
	6	3,4	1733.6±7.1
	7	3,4	1727.9±5.8
	11	3,4	1733.5±4.0
1.6-Mev La^{140}	10	7,3	1595.0±5.7

a. The experiments are described in Table 3.

b. Calibration energies are labeled numerically in Table 2.

c. Interpolations are based on channel numbers such as those in Table 4 using the calibration energies of Table 2.

Table 6 shows the average values obtained from the results of Table 5, as well as the results of the chi-square consistency tests. The averages and errors quoted were obtained from Eqs. 3 and 4. The average values of the unknowns should be compared to the literature values quoted in Table 1. The results of the chi-square tests of Table 6, when combined into an over-all test, are interpreted to mean that for the whole experiment random errors have been underestimated by less than 20%, which is the over-all increase in estimated values which would be necessary to produce chi-square values indicating $P(\chi^2) \cong 0.5$.*

The results in Table 6 for Cs^{137}, Bi^{207}, La^{140} and Na^{24} may be compared with the accepted values in Table 2 to give an indication of the accuracy of the experiments performed and the validity of the assumption that propagated estimated random errors yield a usable error estimate. Energies for Na^{24} (and La^{140}) agree well if the questionable double-escape data are ignored, while those for Bi^{207} and Cs^{137} are outside the quoted error. A chi-square test comparing known and measured values indicates a probability of 0.15 that deviations would be larger if the quoted errors hold.

Table 7 lists final output energies for the unknowns, with values rounded and errors from Table 6 enlarged in two cases by an amount appropriate to make the experimental values internally consistent.**

---

*This test is performed by summing all the χ^2 values for the individual lines and comparing the result to the total number of degrees of freedom. One obtains $\chi^2_\nu/\nu = 51.2/38 = 1.35$ ($P = 0.09$, showing reasonable over-all consistency). If each individual estimated error were increased by 15%, this over-all consistency test would yield $P = 0.5$.

**This process amounts to a determination of error purely on the basis of scatter between the various experiments, using relative weights based on the estimated errors in the measurements. The modification of these errors was performed to allow quotation of the largest plausible standard error. (If the same criterion were applied to the other measurements, the quoted errors would be slightly reduced.)

Table 6. Summary of Averaged Results; Consistency Tests

Source	$\bar{E} \pm \sigma(\bar{E})$ (kev) (a)	N, Number of Values Averaged	χ^2_{N-1}	$P(\chi^2, N-1)$ (b)
	Unknown Transition Energies			
Y^{88}	898.8 ± 1.2	9	4.6	0.7
	1840.1 ± 1.4[c]	11	21.9	0.015
Mn^{54}	834.7 ± 1.1	4	0.83	0.99
Zn^{65}	1113.9 ± 2.1[c]	3	7.6	0.02
	Known Transition Energies			
Cs^{137}	664.3 ± 1.3	3	2.8	0.25
Bi^{207}	1067.0 ± 2.1	3	0.29	0.98
Na^{24}	1369.2 ± 1.7	8	6.2	0.51
$(Na^{24}-2m_e)$	1727.4 ± 2.3	5	7.4	0.13[d]
$(Na^{24}-2m_e)$	1732.0 ± 3.0	3	0.68	0.97[e]
La^{140}	1595 ± 6	1		

a. These values were obtained from Eqs. 3 and 4 using the input values from Table 5.

b. See p. 22 for definition of symbols.

c. Because of the apparent inconsistency indicated by the associated χ^2 test, a larger final error is quoted in Table 7.

d. This includes two sets of data using Configuration 1 in which systematic line-shape errors are thought to have occurred.

e. Data using Configuration 1 is not included in these values.

Table 7. Final Output Values for the Unknown Energies

Source	Energy (kev)	Standard Error (kev)
Y^{88}	898.8	1.2
Y^{88}	1840.0	2.0[b]
Mn^{54}	834.7[a]	1.1
Zn^{65}	1114.0	4.0[b]

a. Note, however, Katoh's recent result of (837.9±0.3) kev (see footnote in the introduction).

b. If the errors on each measurement of this energy were increased by a fixed percent so as to make the consistency tests of Table 6 yield P = 0.5, then Eq. 4 would have yielded this standard error (see footnote ** on p. 27).

IV. CONCLUSIONS

Though for readily available long-lived sources, scintillation spectroscopy can seldom compete with more precise methods for measuring the photon energies from radionuclides, reasonably good results can be obtained if sufficient care is taken. Table 7 shows the final results of the experiments described in this report. Quoted errors are smaller than literature values except for Zn^{65}.

Since Y^{88} is an extremely useful source, its energies should be measured with sufficient accuracy (± about 0.5 kev) to allow its general use as a calibration source. Such a measurement probably cannot be performed using scintillation spectroscopy.

In order to produce the measurements with the internal consistency described in Table 6, it was necessary to compensate the nonlinearities of the pulse-

height analysis system by using a simple method adequate only for energy analysis. This compensation appears to have been quite successful, but more precise results could have been attained if such nonlinearity were unobservably small.

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