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ENERGY REMOVED FROM PRIMARY PROTON AND NEUTRON BEAMS BY TISSUE

W. A. Gibson

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Abstract

The energy removed from primary nucleon beams with energies between 10 and 1000 Mev as they pass through biological tissue is calculated. It is shown that for neutrons with energies above 15 Mev and for protons above 300 Mev the major energy removal mechanism is nuclear absorption of the primary nucleon and that the importance of this process increases with increasing nucleon energy. A qualitative discussion is also given of the biological importance of the secondary nucleons and of the nuclear recoils resulting from the absorption process.

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I. Introduction

A detailed study of radiation shielding for high-energy accelerators and manned space vehicles requires a knowledge of the interaction of nucleons with biological tissue. Calculations of the physical and biological dose deposited by neutrons[1-3] and protons[4] incident on tissue have shown that for neutrons with energies between 1 kev and 10 Mev the main energy-loss mechanism is elastic collisions with the hydrogen in tissue and for protons with energies between 0.01 and 200 Mev it is ionization. It is the purpose of this report to point out that at higher energies complex interactions take place between the nucleons and nuclei and that these interactions are important energy-loss mechanisms. This is demonstrated by quantitative results of a calculation of the energy removed by tissue from a primary* nucleon beam and a qualitative discussion of the final deposition of this energy in the tissue. Because of a lack of sufficient information on the deposition processes no quantitative results on the deposited energy can be presented. Throughout the calculation the composition of tissue is assumed to be represented by the formula $C_7H_{70}O_{32}N_2$ (Ref. 5).

II. Energy Loss from Primary Nucleon Beams

Loss from Neutron Beam

The energy loss from a primary neutron beam for energies above 10 Mev was assumed to be due to two effects: (1) absorption by complex nuclei, where absorption is assumed to include all nuclear reactions except elastic scattering, and (2) elastic scattering from hydrogen nuclei (protons). Other energy-loss mechanisms, such as the $H(n,\gamma)D$ reaction

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1. Protection Against Neutron Radiation up to 30 Million Electron Volts, Nat. Bur. Standards (U.S.) Handbook, Vol. 63 (1957).
2. W. S. Snyder and J. Neufeld, Health Physics Progress Report Period Ending July 31, 1956, ORNL-2151 (1956).
3. M. L. Randolph, Rad. Research 7, 47 (1957).
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5. D. E. Lea, Actions of Radiations on Living Cells, Cambridge University Press, New York, 1947 (2d ed., 1955).

*"Primary" nucleons are those in the incident beam as opposed to "secondary" nucleons produced by interactions of the primary nucleons.

and elastic scattering by complex nuclei, are unimportant in the energy region considered and were neglected.

The calculation of the neutron absorption required a knowledge of the absorption cross sections for carbon, nitrogen, and oxygen. It was found that for these elements adequate data existed only for carbon;[6-8] therefore, it was necessary to obtain the cross sections for nitrogen and oxygen by extrapolating the carbon cross section. The extrapolation was executed by using the following equations:

$$\sigma_a = \pi(R + \lambda\!\!\!^{-})^2, \tag{1}$$

$$R = aA^{1/3} + b, \tag{2}$$

where σ_a is the absorption cross section, R is the radius of the nucleus, A is the atomic number, $\lambda\!\!\!^{-}$ is the de Broglie wave length divided by 2π, and the constants a and b were determined from the measured aluminum[8] and carbon cross sections at 55 and 140 Mev. The average of these determinations gave a = 1.43 and b = -0.90. Equations 1 and 2 were combined to obtain an expression for the unknown cross section $\sigma_{a,x}(E)$ at a particular energy E in terms of the carbon cross section $\sigma_{a,C}(E)$ at the same energy. The result is

$$\sigma_{a,x}(E) = (1.43A_x^{1/3} - 0.90 + \lambda)^2 \, \sigma_{a,C}(E)/(1.43A_C^{1/3} - 0.90 + \lambda\!\!\!^{-})^2.$$

The resulting cross section for each element is shown in Fig. 1. It is important to note that at about 100 Mev the cross sections become flat.

The calculation of the energy lost by neutrons scattered elastically from hydrogen nuclei (protons) was performed by assuming that the scattering is isotropic in the center-of-mass system, and for this case the

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7. G. P. Millburn, W. Birnbaum, W. E. Crandall, and L. Schecter, Phys. Rev. 95, 1268 (1954).
8. R. G. P. Voss and R. Wilson, Proc. Roy. Soc. (London) A236, 41 (1956).

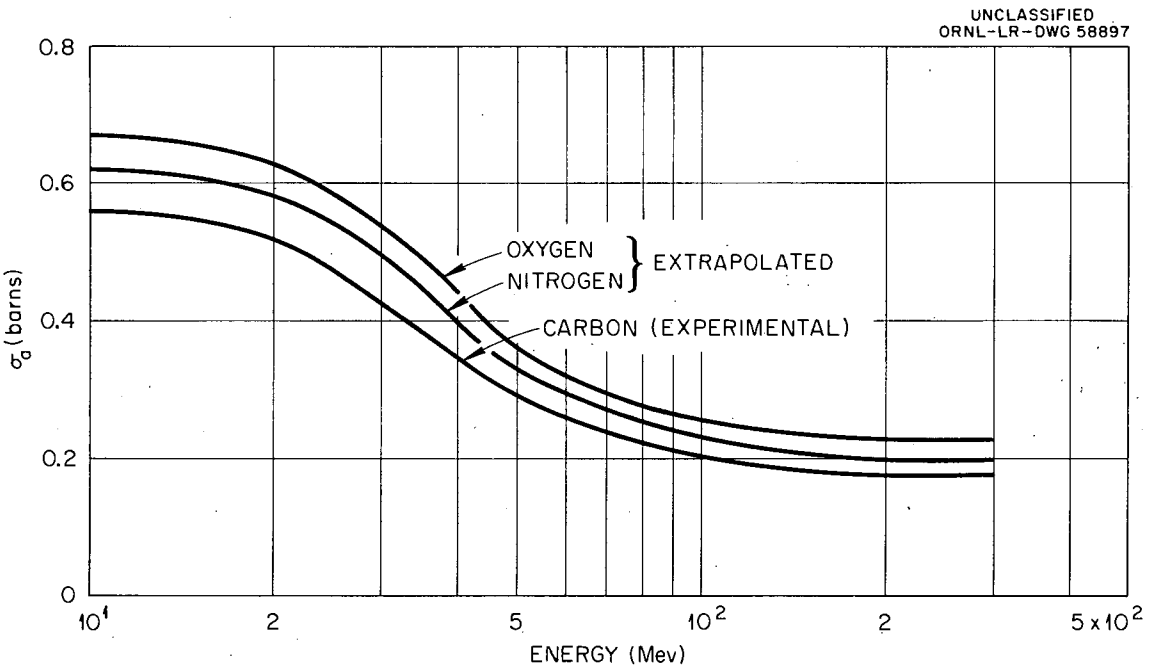

Fig. 1. Neutron Absorption Cross Sections for Carbon, Oxygen, and Nitrogen

average neutron energy loss in the laboratory system is one-half the incident neutron energy. The total elastic (n,p) cross section (taken from Ref. 9) is shown in Fig. 2. For purposes of comparison, the carbon absorption cross section for nucleons is also shown.

The energy removed, ΔE, is given by

$$\Delta E = 57.6 \times 10^{-6} E_0 \left[\frac{\sigma_{el} n_p}{2} + \sum_x \sigma_{a,x} n_x \right] \frac{\text{rads/hr}}{\text{neutron/cm}^2 \cdot \text{sec}},$$

where E_0 is the energy of the incident nucleon (in Mev), σ_{el} is the appropriate elastic nucleon-nucleon cross section (in cm^2), n_p is the number of protons per cubic centimeter of tissue, $\sigma_{a,x}$ is the absorption cross section (in cm^2) for the element x in the tissue, and n_x is the number of atoms of x per cubic centimeter.

The results are shown in Fig. 3. At low energies (between 10 and 15 Mev) the loss by elastic scattering with protons remains the dominant effect, but at higher energies the energy removal from the primary beam is due mainly to absorption. This is the result of the leveling off of the absorption cross sections which causes a rapid and almost linear increase of energy removal with neutron energy. The leveling off of the inelastic nuclear cross section causes a rapid and almost linear increase of energy removal with neutron energy above 100 Mev.

At 10 Mev, where the present calculation can be compared with two of the earlier calculations,[1,2] the results are 15 to 25 percent higher than those given in the earlier reports. The discrepancy can be explained by the fact that this calculation is expected to be an upper limit and also by the fact that the earlier calculations neglected all nonelastic events, which are significant at 10 Mev. (The proton dose calculations for 10 Mev reported below are more accurate since the major portion of the dose results from ionization which is calculated from stopping power curves[10] for ionization collisions which are accurate to within a few percent.) Comparison of this calculation with that of Randolph[3] at 14.1 Mev indicates the present

9. S. J. Lindenbaum, Annual Review of Nuclear Science, 7, 317 (Annual Reviews, Inc., Palo Alto, California, 1957).
10. M. Rich and R. Madey, Range Energy Tables, UCRL-2301 (1954).

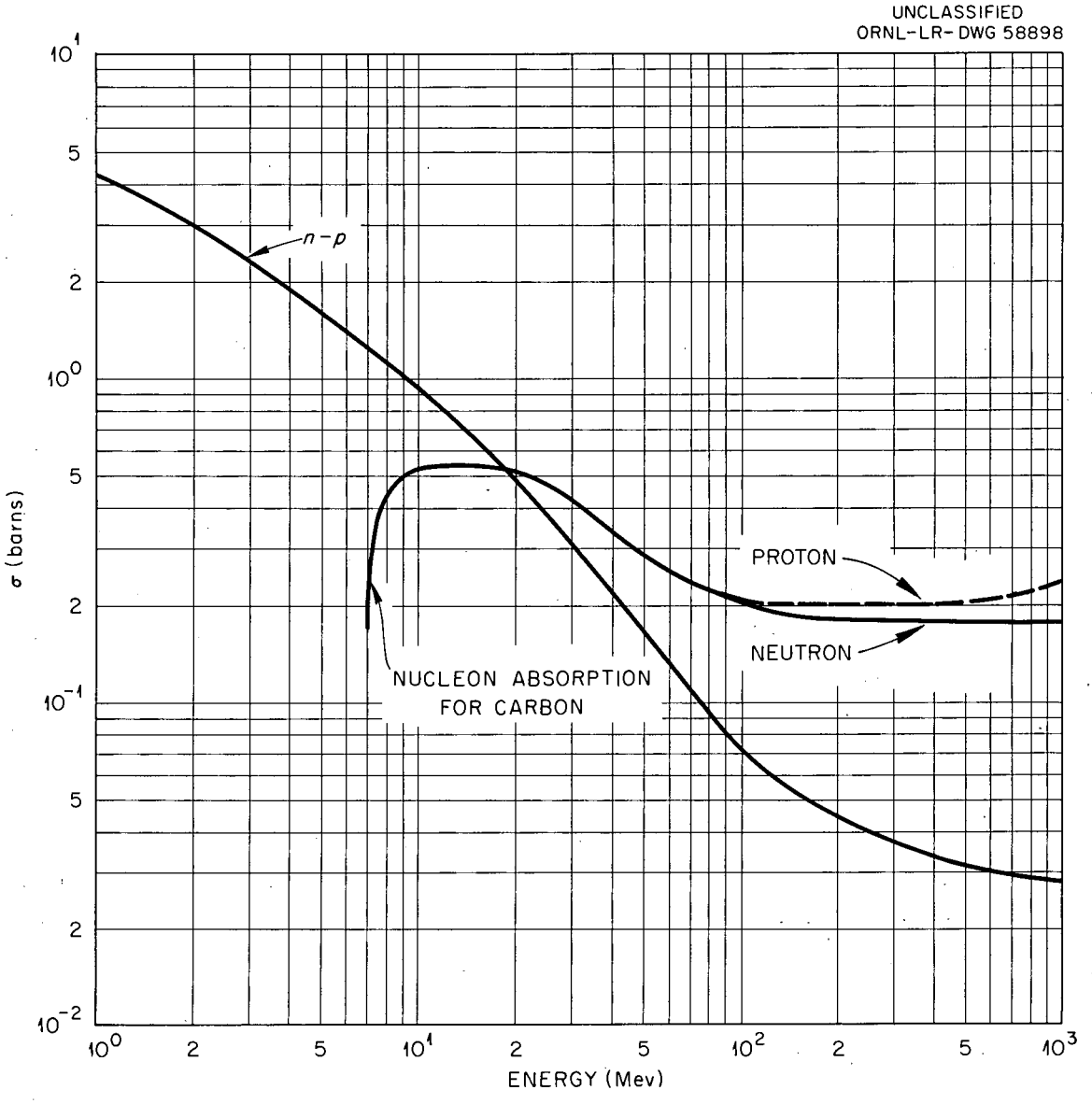

Fig. 2. Comparison of Elastic n-p Cross Section with Nucleon Absorption Cross Section for Carbon

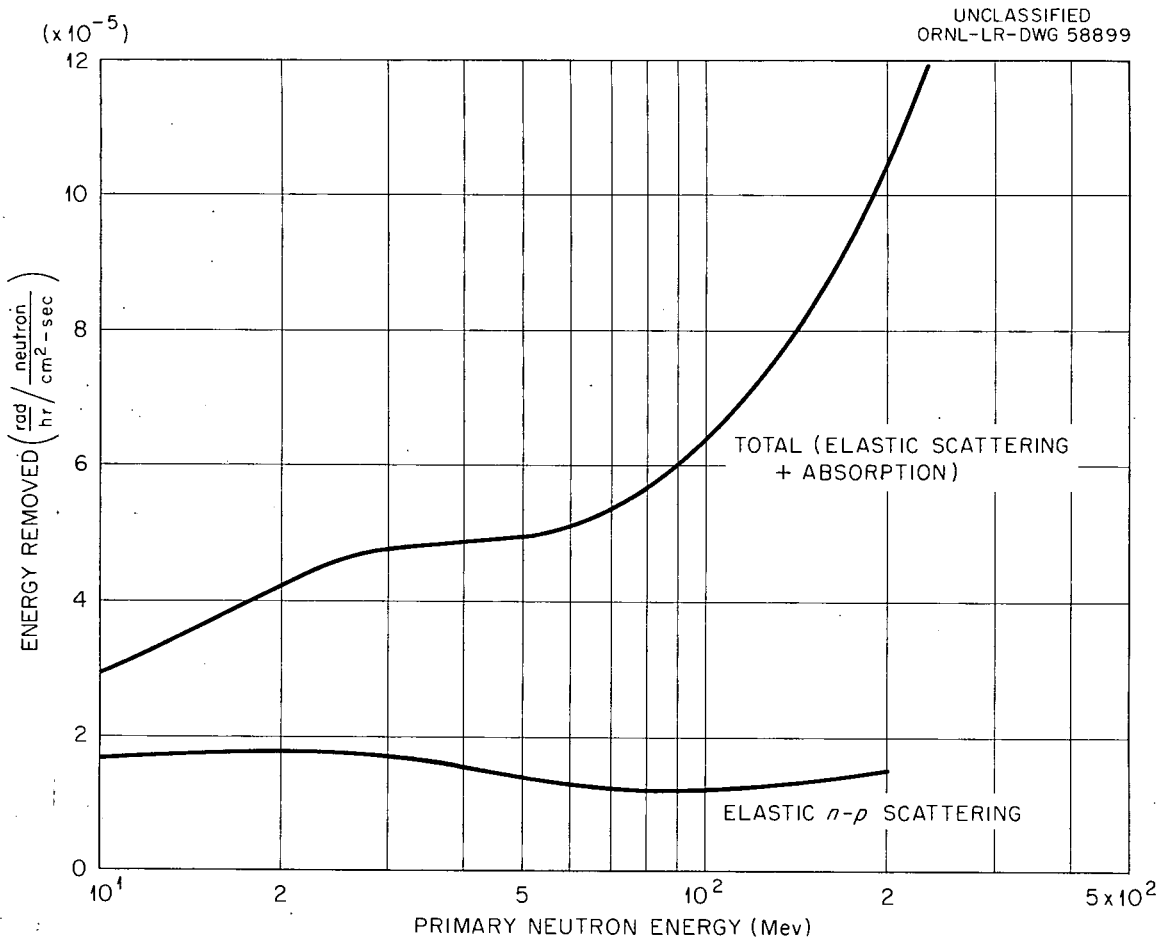

Fig. 3. Energy Removed from Primary Neutron Beam by Tissue

calculation considerably overestimates the dose; however, Randolph did not include gamma rays in his dose.

Loss from Proton Beam

The energy loss from a primary proton beam for energies above 10 Mev was also assumed to be due to two effects: (1) absorption, and (2) ionization. For energies less than 300 Mev, the major mechanism is ionization; however, at higher energies the loss by absorption becomes important. As is shown by Fig. 2, the proton absorption cross section for complex nuclei[7] (i.e., carbon in the figure) in the energy range from 10 to 300 Mev is roughly equal to the neutron absorption cross section, and, hence the energy lost by protons within this energy range through absorption is approximately equal to the energy lost by neutrons through absorption. Above 300 Mev, the proton absorption cross section is somewhat larger than the neutron cross section, which results in a 30 percent increase in energy removal for protons over neutrons at 1 Bev. The relative importance of the various effects is shown in Fig. 4, which also gives the total energy removed from the primary proton beam by the combined ionization and absorption effects.

The energy deposited by ionization is

$$\Delta E = 57.6 \times 10^{-6} \sum_{x} (\mathrm{LET})_x \, d_x,$$

where $(\mathrm{LET})_x$ is the linear energy transfer* of element x in Mev/g/cm^2 and d_x is the density of the element x in g/cm^3 in tissue.

It might be assumed that since the LET for ionization of high-energy protons is relatively small the RBE (relative biological effectiveness) would also be small. However, according to Fig. 4 the removal of the energy from the primary proton beam by absorption becomes greater than the removal by ionization at energies above approximately 300 Mev and it is necessary to consider absorption as the major interaction when determining the RBE.

III. Deposition of Nucleon Energy in Tissue

While the amount of energy deposited locally in tissue by a nucleon beam through ionization and elastic nucleon-nucleon scattering can be

*Note that the terms "stopping power" and "LET" are synonomous.

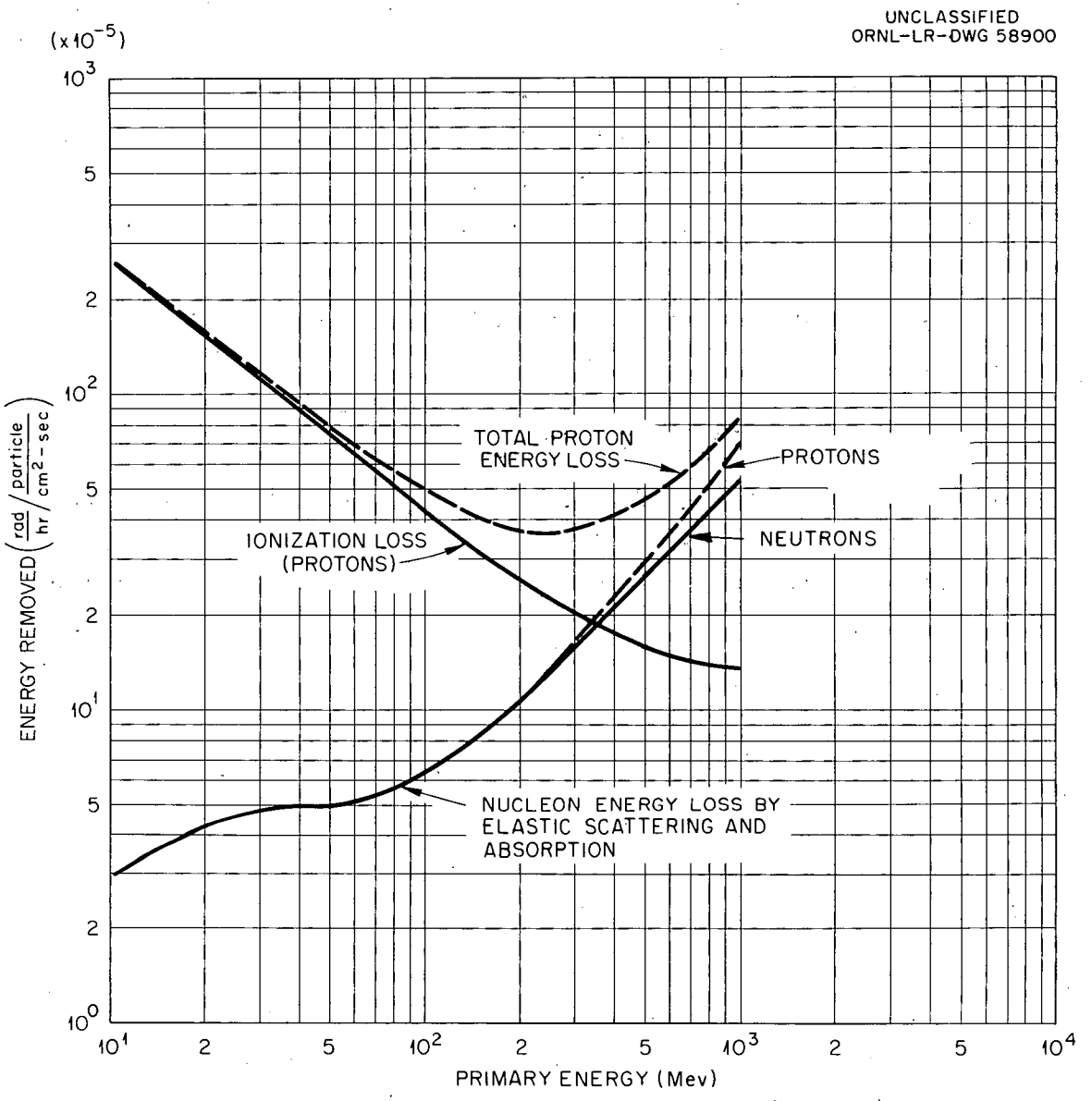

Fig. 4. Energy Removed from Primary Proton and Neutron Beams by Tissue

calculated quantitatively, a lack of information describing nuclear interactions with the tissue make a quantitative calculation of the local energy deposition following absorption impossible. Furthermore, since the energies of the particles emitted following absorption are not known, the RBE of the particles cannot be calculated as can be done in the case of direct ionization and nucleon-nucleon scattering.

However, a qualitative discussion of the energy deposition and RBE of the particles resulting from absorption is given below.

(1) Recoil of the Absorbing Nucleus. The energy absorbed in the recoil is very small,[11] but the high RBE for heavy ions[12] may result in a significant biological dose. The lack of calculations for the momentum imparted to low atomic weight nuclei make accurate estimates of energy deposition by this process impossible.

(2) High-Energy Cascades. Several high-energy nucleons may be emitted by the absorbing nucleus, the number and energy depending upon the energy of the incident nucleon and the atomic number of the target nucleus.[13,14] The number of neutrons and the number of protons emitted are roughly equal, and the total number of nucleons emitted per event varies from about 3 to 5 for bombarding energies of 300 Mev and 2 Bev, respectively. Each of these secondary nucleons will have a higher LET and may have a significantly higher RBE than the primary nucleon; hence, the production of several lower energy nucleons may produce an increase in the local biological dose of several times that caused by the primary protons. There are no calculations which give energy spectra and particle multiplicity for cascade nucleons from low atomic weight elements such as those found in tissue.

(3) Evaporation Nucleons. After the cascade process the nucleus boils off nucleons with average energies of the order of 1 to 2 Mev.[15] These low-energy nucleons will deposit most of their energy locally

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with a large RBE. The ratio of the number of neutrons to the number of protons given off is difficult to calculate and so far no such calculations have been made for low-Z elements because of the dependence of the ratio on the shell structure and the small number of excitation levels.[16] The neutron-to-proton ratio for the evaporation nucleons for carbon has been determined experimentally by Gross[17] to be about 1; he also found that the number of evaporation nucleons is very roughly equal to the number of cascade nucleons.

It should also be mentioned that heavier particles such as alpha particles and lithium nuclei may also be boiled off which will have an even higher RBE than the secondary nucleons.

IV. Conclusions

For neutrons with energies above 15 Mev and protons above 300 Mev the removal of energy from the primary beam by absorption is greater than the removal through elastic scattering and ionization, and as the primary energy increases the importance of the absorption events increases. The fact that the secondary particles resulting from absorption have, on the average, much lower energies means that more energy is deposited in the tissue and with a larger RBE than would be expected from ionization and elastic scattering of the primary beams alone. The neglect of these absorption processes will lead to a gross underestimate of the biological damage done by the radiation.

An accurate study of this problem must begin with a thorough understanding of the energy and particle spectra, as well as the recoil spectrum for complex nuclei, associated with the absorption process. With this knowledge, along with the geometry of the biological system and the RBE assigned to each particle, one can, in principle, calculate the biological dose deposited by high-energy neutrons and protons.

It should be noted in the case of shielding problems that the interaction of high-energy neutrons with tissue is an important area of investigation since high-energy neutrons are produced by the interaction of high-energy protons with the shield material.

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16. L. Dresner, private communication.
17. E. Gross, Absolute Yield of Low-Energy Neutrons from 190-Mev Proton Bombardment of Gold, Silver, Nickel, Aluminum, and Carbon, UCRL-3330 (1956).

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