# Photoneutron Production Excitation Functions to 320 Mev

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Photoneutron yields from eleven elements were obtained from bremsstrahlung of maximum energy 13.5 to 320 Mev with the reaction, $Cu^{63}(\gamma, n)Cu^{62}$, as a monitor. The yield data were analyzed by a photon difference method to give the excitation functions for photoneutron production. Most of these excitation functions showed the typical resonance shape in the 20-Mev region, a low but finite "tail" to about 80 Mev and a large rise from there to 320 Mev. With the use of a calculated neutron multiplicity $\int_0^{80}\sigma dE$ for tantalum was found to be 5.1 Mev-barns, somewhat higher than $\int_0^{\infty}\sigma dE$ predicted by Levinger and Bethe for the electric dipole interaction. The rise above 80 Mev is probably due to mesonic interactions. At the meson threshold, with data for the neutron multiplicity from $\pi^-$ absorption, the photon absorption cross section was found to obey the relation,

$$\sigma = 0.32A^{1.3}\times 10^{-28}\ \text{cm}^2.$$

## INTRODUCTION

KNOWLEDGE of the magnitude and energy dependence of photonuclear absorption cross sections is basic to the understanding of the interaction of high-energy quanta with nuclei. Previous experimenters,[1-7] measuring induced activities, have shown that the excitation functions for $(\gamma,n)$ and $(\gamma,p)$ reactions have large peaks in the neighborhood of 20 Mev. The magnitude of the photonuclear interaction above this 20-Mev region is difficult to measure quantitatively by induced activities because of the limited number and small yield of those reactions which can be measured by this technique. The method of detecting emitted neutrons, however, sums over all the individual reactions to give a fairly quantitative picture of the high-energy photon absorption process.

An indication that large photonuclear interactions involving neutron production exist above the low-energy peaks was found by Eyges[8] from an analysis of an experiment of the authors on neutron production from 320-Mev bremsstrahlung.[9] Kerst[10] also has noted larger neutron yields from 320- than from 22-Mev bremsstrahlung. These results prompted the present determination of photoneutron production cross sections from the region of the low-energy peaks to 320-Mev.

Neutron yields from eleven elements were obtained from 13.5 to 70 Mev with the 70-Mev General Electric synchrotron of the University of California Hospital in San Francisco, and from 80 to 320 Mev with the 320-Mev synchrotron of the University of California Radiation Laboratory at Berkeley. The neutron yields were taken relative to the yield of the $Cu^{63}(\gamma,n)Cu^{62}$ reaction at each bremsstrahlung energy, and cross sections for neutron production were deduced by a photon difference method.

## EXPERIMENTAL PROCEDURE

The neutrons were detected at 90 degrees to the beam with a boron trifluoride proportional counter in a long counter geometry of paraffin.[11] The active volume of the counter was 10 inches long, and the paraffin cylinder in which it was embedded was 15 inches long by 8 inches in diameter. This type of counter is reported to be uniformly sensitive to neutrons of from 100 kev to 5 Mev entering parallel to its axis, its sensitivity dropping to 67 percent of maximum for 14- and 18-

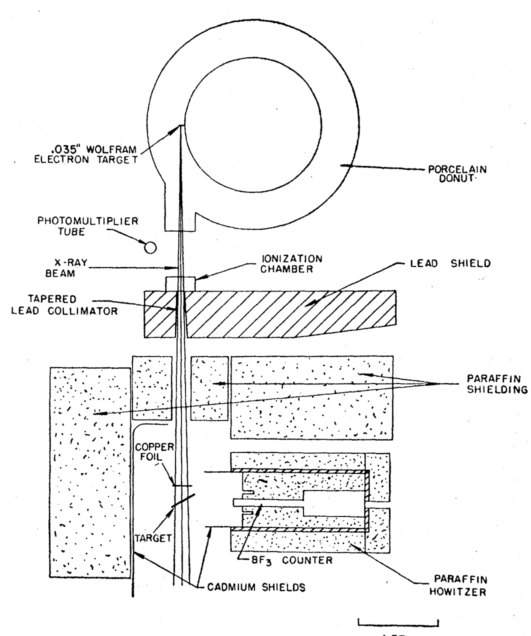


FIG. 1. Schematic overhead layout of the 70-Mev synchrotron and the experimental arrangement.

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[1] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **73**, 1156 (1948).
[2] G. M. Almy and B. C. Diven, Phys. Rev. **80**, 407 (1950).
[3] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).
[4] J. Halpern and A. K. Mann, Phys. Rev. **84**, 840 (1951).
[5] R. Sagane, Phys. Rev. **85**, 926 (1952).
[6] Haslam, Johns, and Horsley, Phys. Rev. **82**, 270 (1951).
[7] L. Katz and A. Cameron, Phys. Rev. **84**, 1115 (1951).
[8] L. Eyges, Phys. Rev. **86**, 325 (1952).
[9] Terwilliger, Jones, and Jarmie, Phys. Rev. **82**, 820 (1951).
[10] D. W. Kerst, private communication.
[11] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

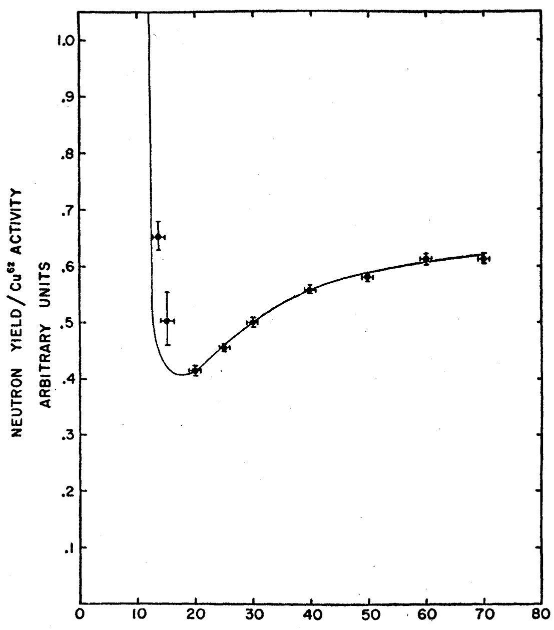


FIG. 2. Neutron yields from copper per unit of induced copper activity as a function of $E_0$, the maximum bremsstrahlung energy.

Mev neutrons.[12] This response is altered to favor lower energy neutrons by the proximity of the target to the face of the counter.

With both synchrotrons the beam pulse was short, less than 20 microseconds. However, neutron diffusion in the paraffin, with a half-life of about 175 microseconds, made possible high neutron counting rates without large corrections for counter dead time. The counter pulses were clipped to 0.5 microsecond to minimize the pileup of neutrons and of electrons associated with the beam pulse. Electron pulses were biased out by operating the neutron counter at the low-voltage end of its plateau.

A plan view of the experimental arrangement used with the 70-Mev synchrotron is shown in Fig. 1. The synchrotron beam was collimated by a tapered rectangular aperture in an eight-inch lead wall in front of the synchrotron. In addition, 1000 pounds of paraffin faced with cadmium were used to shield the counter from the neutron background.

The beam monitor, a 0.016-inch copper foil, was bombarded along with each target element at each energy. The bombardments were of two-minute duration except at 13.5 Mev where they were four minutes. After a two-minute transfer time, the positron activity of the copper foil was counted for two minutes in a reproducible geometry by a 1B85 Victoreen thyrode Geiger counter.

Similar geometry and procedure were used with the Berkeley synchrotron. In this case at each energy the copper foil method was used to calibrate the beam integrating ionization chamber. Then this chamber was used as a secondary monitor for the neutron counting. This calibration was repeated every time the energy setting was changed. Here the copper foils were bombarded for ten minutes and, after a two-minute change-over, counted for ten minutes.

The beam energy was varied on both machines by maintaining the magnet current pulse at its maximum value and turning off the accelerating voltage before peak magnetic field. The electron energy at the time of radiation was found from the time of rf turnoff with the assumption of a sinusoidally varying magnetic field. The energy at maximum field was determined at Berkeley by Powell *et al.*[13] and by magnetic field measurements at San Francisco. The thresholds for the $C^{12}(\gamma,n)$ and $Cu^{63}(\gamma,n)$ reactions were determined with the San Francisco machine and agreed with known values.

## DATA AND ERRORS

Neutron yields per unit of induced copper activity were obtained for each element with the synchrotron of the University of California Hospital for values of maximum bremsstrahlung energy of 13.5, 20, 25, 30, 40, 50, 60, and 70 Mev. Some points were also obtained at 15 and 19 Mev. Elements studied were the natural isotopic mixtures of Be, C, Al, Fe, Cu, Mo, Ag, Ta, W, Pb, and U. The targets were from 0.2 to 0.7 shower unit thick.

With the Berkeley synchrotron, data were taken for values of maximum bremsstrahlung energy of 80, 120, 160, 200, 240, 280, and 320 Mev. Neutron yields were obtained there with similar targets of the above eleven elements.

### 70-Mev Synchrotron

Each data point above 20 Mev was taken twice and the two yield values were averaged. A typical set of yield data, that for Cu, taken with the San Francisco machine, is shown in Fig. 2. The errors shown are the probable errors and the energy uncertainty which was about one Mev. The yield curve drawn results in a smooth cross section curve (see section on Analysis). The sharp rise of the curve at low energies is due to the lower $(\gamma,n)$ threshold in $Cu^{65}$(9.7 Mev) than in the monitoring isotope, $Cu^{63}$(10.9 Mev).

Twenty-three bombardments of Cu with 40-Mev bremsstrahlung were spaced throughout the experiment to obtain an estimate of the probable error due to random fluctuations of experimental conditions. The results of these runs and the counting errors indicated that all elements except C and Al had probable errors under 1.6 percent for energies 20 Mev and over, and under 8 percent for lower energies. The C and Al errors were under 4 percent at energies above 20 Mev.

Effects such as anisotropy in neutron angular distri-

[12] Barschall, Rosen, Taschek, and Williams, Revs. Modern Phys. 74, 1 (1951).

[13] Powell, Hartsough, and Hill, Phys. Rev. 81, 213 (1951).

bution, neutron scattering within the target, and scattering of neutrons from the beam into the counter could cause systematic errors in the yield points above 25 Mev of as much as 15 percent for Be, C, and Al, but under 2 percent for the higher $Z$ elements.

### 320-Mev Synchrotron

The yield data for Cu from the Berkeley synchrotron are shown in Fig. 3. Since the counting rates were low, no correction was made for neutron counter dead time, which could cause errors of at most 3 percent. Most data points were repeated to insure consistency. These checks and the counting statistics indicated that all data points had probable errors of less than 2 percent. The systematic errors are similar to those for the San Francisco synchrotron.

The maximum energy of the Berkeley synchrotron is $322\pm6$ Mev.[13] It has been taken here as nominally 320 Mev. The relative energy settings were accurate to about 6 Mev.

## BREMSSTRAHLUNG

Fundamental to the determination of excitation functions is knowledge of the bremsstrahlung spectra. The spectra used in this experiment for the analysis were obtained by graphically interpolating the representative curves of the basic Bethe-Heitler formula which Rossi and Greisen[14] have plotted for lead, with screening taken into account. Each spectrum is for a thin target and is an average over all angles of the outgoing photons. Schiff[15] has shown that in a finite target multiple scattering causes the spectrum to be independent of angle, so that this integrated Bethe-Heitler spectrum is satisfactory for any fraction of the beam used. Although the Bethe-Heitler formula was derived with the use of the Born approximation, which is not valid for heavy elements, Davies and Bethe[16] have recently shown that the correction term is an additive constant, which would change the magnitude of the bremsstrahlung cross section about 10 percent and the shape considerably less. The bremsstrahlung shape predicted by the Bethe-Heitler formula has been experimentally verified at high energies to within 10 percent.[13,17–19]

Eyges[20] has extended the Bethe-Heitler expression to thick targets by calculating the corrections due to cascade showering. Considering only first-order correction terms, he obtained

$$V\phi'(E_0,E)=V\phi(E_0,E)[1-\tfrac{1}{2}T\{\sigma(E)-\ln(1-V)\}], \quad (1)$$

where $\phi$ is the Bethe-Heitler spectrum, $\phi'$ is the corrected spectrum, $V=E/E_0$, $E_0$ the energy of the incident electrons, $E$ the energy of the radiated quantum, $T$ the target thickness expressed in radiation lengths, and $\sigma(E)$ the cross section of the target material per radiation length for absorption of quanta of energy $E$.

If the x-ray beam is collimated, Eyges' correction must be modified because of multiple scattering in the target. The average target thickness traversed by an electron with its direction of motion inside the cone subtended by the collimator was used as an effective target thickness $\bar{t}$. From the Williams scattering expression[21] $\bar{t}$ was found to be[22]

$$\bar{t}=\alpha\int_0^T\frac{e^{-\alpha/t}}{t}dt+(1-e^{-\alpha/T})T,$$

where

$$\alpha=\frac{1}{2N}\left(\frac{\theta E_0}{9.2Ze^2}\right)^2, \quad (2)$$

$\theta$ is the half-angle subtended by the collimator from the target, and $N$ is the target density in atoms $cm^{-2}$ per radiation length.

The equation for the final corrected spectrum is

$$V\phi'(E_0,E)=V\phi(E_0,E)\times[1-(T-\tfrac{1}{2}\bar{t})\sigma(E)+\tfrac{1}{2}\bar{t}\ln(1-V)]. \quad (3)$$

In both the Berkeley and San Francisco machines the electrons were assumed to traverse the entire target and not just graze the edge. The agreement of the

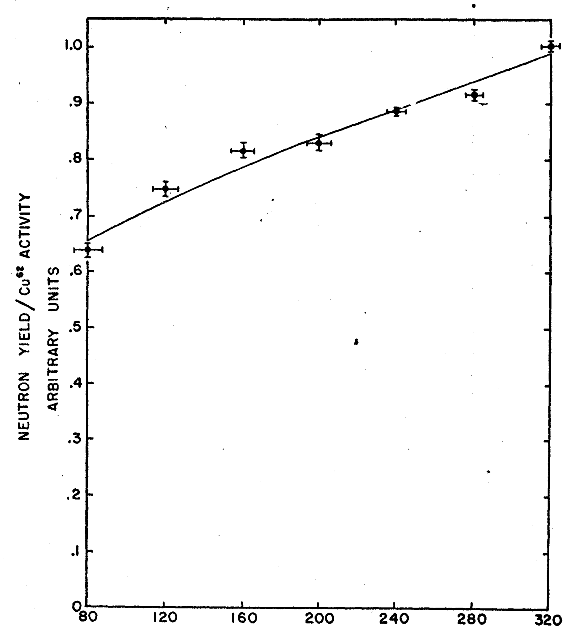


FIG. 3. Neutron yields from copper per unit of induced copper activity as a function of $E_0$, the maximum bremsstrahlung energy.

[14] B. Rossi and K. Greisen, Revs. Modern Phys. **13**, 253 (1941).
[15] L. I. Schiff, Phys. Rev. **70**, 87 (1946).
[16] H. Davies and H. A. Bethe, Phys. Rev. **87**, 156 (1952).
[17] J. W. Dewire and L. A. Beach, Phys. Rev. **83**, 476 (1951).
[18] R. H. Stokes, Phys. Rev. **84**, 991 (1951).
[19] C. R. Emigh, Phys. Rev. **86**, 1028 (1952).
[20] L. Eyges, Phys. Rev. **81**, 981 (1951).
[21] E. J. Williams, Phys. Rev. **58**, 292 (1940).
[22] L. W. Jones, University of California Radiation Laboratory Report UCRL-1916 (unpublished).

angular spread measurements of Rosengren[23] on the Berkeley synchrotron and Adams[24] on the San Francisco synchrotron with those of Lanzl and Hanson[25] using an externally deflected electron beam indicates that this assumption is justified.

For the energy ranges used, the shape correction to the Bethe-Heitler spectrum was at most 20 percent for the Berkeley 320-Mev synchrotron with a 0.020-inch Pt target and 10 percent for the San Francisco 70-Mev synchrotron with a 0.035-inch W target. Errors in the assumed bremsstrahlung shape affect the derived cross sections linearly.

This calculated bremsstrahlung spectrum is that falling on the front face of the target element being bombarded. The spectrum was further corrected for photon absorption in each neutron target, the correction amounting to as much as 20 percent for some of the targets for high-energy quanta. The targets were not so thick, however, that significant numbers of neutrons were produced from secondary shower quanta.

## ANALYSIS

The neutron yields represented the relative values of the ratio

$$\int_0^{E_0} \sigma_n(E)\phi(E_0, E)dE \bigg/ \int_0^{E_0} \sigma_c(E)\phi(E_0, E)dE, \quad (4)$$

where $\sigma_n(E)$ is the cross section for neutron production and $\sigma_c(E)$ is the cross section for the $Cu^{63}(\gamma, n)Cu^{62}$ reaction. The excitation functions $\sigma_n(E)$ were calculated from the yield curves by a photon difference method, which has been discussed in the literature.[26] This method will be described briefly here.

The difference in yields for two successive values of $E_0$ is due to the difference in their bremsstrahlung spectra $\phi(E_0, E)$, the difference occurring over energies below as well as between the two $E_0$. Therefore, the yield difference must be corrected for the effect of the lower-energy quanta before $\bar{\sigma}_n$, the average cross section for the energy interval, can be obtained. Since each correction term is dependent on the lower-energy cross sections, the $\bar{\sigma}_n$ must be calculated in sequence from low to high energy.

The relative magnitude of each $\phi(E_0, E)$ was calculated from the measured activity of the copper foil monitor with the use of $\sigma_c(E)$. This excitation function has been measured out to 24 Mev by a number of investigators[2,3,27] who monitored their bremsstrahlung with either a calibrated Lucite ion chamber or a pair spectrometer. The shape of their curves agreed to about 10 percent. The curve obtained by Johns *et al.*[3] was used in this analysis. Although their work did not extend above 24 Mev, it indicated that at that energy the cross section was very small. In this analysis the cross section was assumed to be zero above 24 Mev.

The energy increments chosen for the analysis varied from 2.5 to 10 Mev below 70 Mev and were 40 Mev wide above 80 Mev. Above 30 Mev, the yield corrections were usually less than one-half of the yield differences. The $\bar{\sigma}_n$ were assigned to the energy corresponding to the middle of the interval. Since the cross sections are interdependent, errors as small as 2 percent in the chosen yield curves result in oscillations in the successive cross sections. These oscillations were smoothed by successive trail yield curves through the measured yield points. This procedure produces an excitation function which is averaged over neighboring intervals.

The first data point was at 13.5 Mev, and the shapes of the cross-section curves up to that energy were estimated from thresholds and the work of other experimenters on $(\gamma,n)$ excitation functions. These estimated curves were normalized to the calculated excitation functions from the neutron yield at 13.5 Mev.

The excitation functions obtained on the 70-Mev San Francisco synchrotron were normalized to those obtained on the 320-Mev Berkeley synchrotron through the Berkeley yield at 80 Mev. A change of about 1 percent in the ends of the yield curves was required to match the cross-section curves from the two machines.

The variation with $Z$ of the magnitudes of the cross-section curves was determined independently on the two machines through the relative neutron yields. The results from the two machines agreed to within 5 percent; the mean was used for the final relative magnitudes.

The absolute magnitude of the cross-section curves was determined from the results of a previous experiment[9] by the authors on the neutron yields produced by bombardment with 320-Mev bremsstrahlung. The beam was calibrated by Blocker, Kenney, and Panofsky.[28] The neutron yields were determined by comparison with an Argonne calibrated radium-beryllium source. The absolute magnitude calibration is estimated to be accurate to 15 percent.

## RESULTS

The calculated excitation functions are presented in Figs. 4 and 5. The dashed sections represent the estimated curves below 13.5 Mev. Where possible, known cross-section curves by other authors are included on the same graph. The shape and magnitude of the beryllium cross section up to 7 Mev was taken from the theoretical work of Guth and Mullin.[29]

The neutron production cross section $\sigma_n(E)$ used in this experiment may be represented as

$$\sigma_n(E) = \sigma_a(E)\int_0^E \nu(E, \epsilon)P(\epsilon)d\epsilon, \quad (5)$$

[23] J. W. Rosengren, private communication.
[24] G. D. Adams, private communication.
[25] L. H. Lanzl and A. O. Hanson, Phys. Rev. **83**, 959 (1951).
[26] R. Sagane, Phys. Rev. **84**, 586 (1951).
[27] V. E. Krohn, Jr., and E. F. Shrader, Phys. Rev. **87**, 685 (1952).
[28] Blocker, Kenney, and Panofsky, Phys. Rev. **79**, 419 (1950).
[29] E. Guth and C. J. Mullin, Phys. Rev. **76**, 234 (1949).

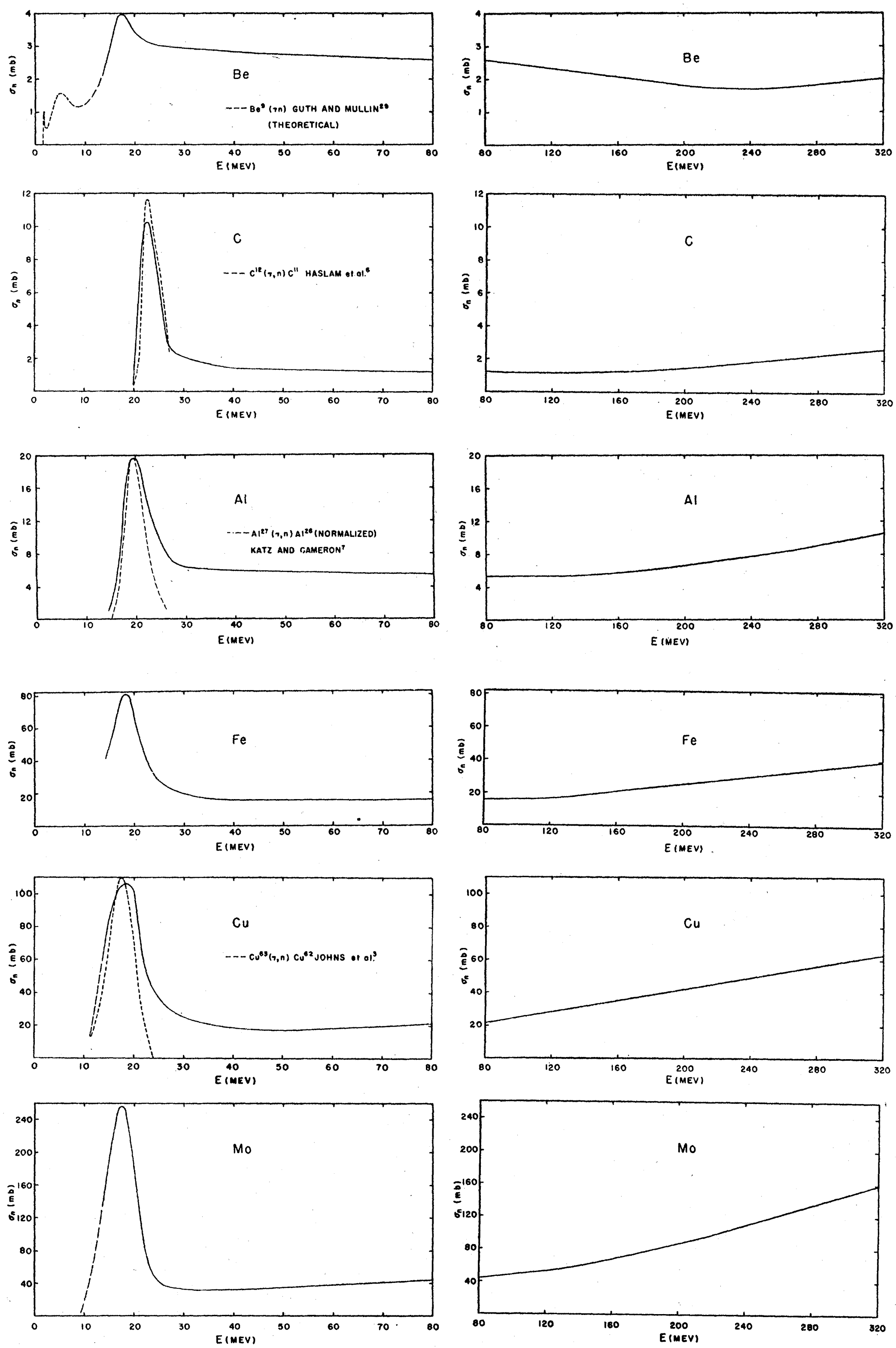


FIG. 4. Curves of cross sections for photoneutron production $\sigma_n$ as a function of quantum energy $E$. The curves are extimated up to 13.5 Mev, the first data point.

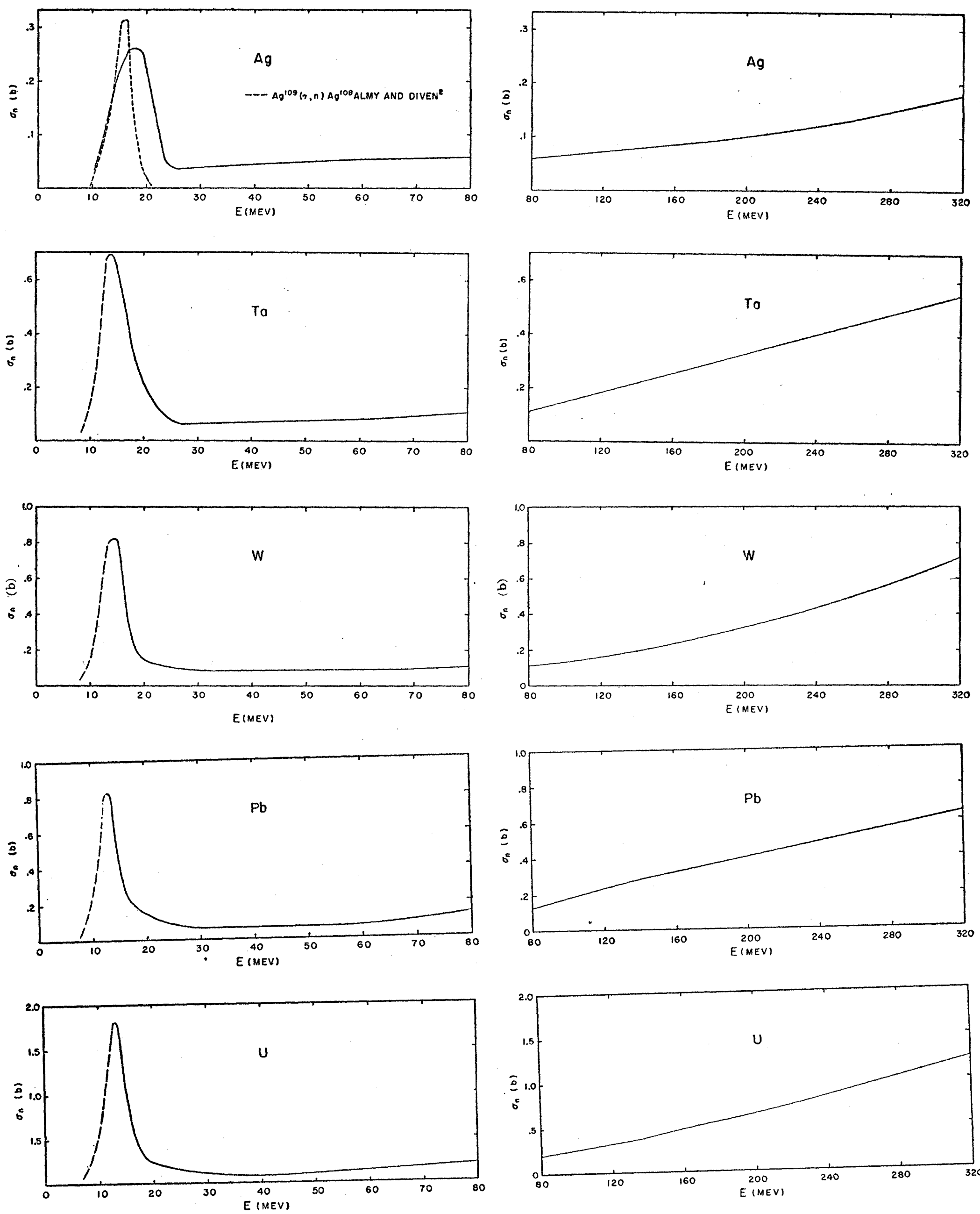


FIG. 5. Curves of cross sections for photoneutron production $\sigma_n$ as a function of quantum energy $E$. The curves are estimated up to 13.5 Mev, the first data point.

where $\sigma_a(E)$ is the photon absorption cross section; $\nu(E, \epsilon)$, the probability that a nucleus, having absorbed a photon of energy $E$, will emit a neutron of energy $\epsilon$; and $P(\epsilon)$, the relative detection efficiency of the neutron counter for neutrons of energy $\epsilon$, being unity for Ra-Be neutrons. If $P(\epsilon)$ were constant, $\sigma_n(E)$ would represent $\sigma_a(E)\nu(E)$, where $\nu(E)$ is the total neutron multiplicity for a nucleus excited to energy $E$. Since, however, $P(\epsilon)$ for 17-Mev neutrons is less than 0.67 of its value for low-energy neutrons, $\sigma_n(E)$ actually represents only a minimum value of $\sigma_a(E)\nu(E)$.

Some estimate of the failure of the assumption that the counter is uniformly sensitive to all neutrons produced may be made by comparison of the neutron yield data[9] with the photoproton data of Levinthal and Silverman[30] and Keck.[31] It is assumed here that the numbers of neutrons and protons of energies well above the Coulomb barrier are approximately equal, and the validity of this assumption is indicated by rough measurements of Keck and Kerst.[32] From this comparison, a maximum of 20 percent of the photoneutrons

[30] C. Levinthal and A. Silverman, Phys. Rev. **82**, 822 (1951).
[31] J. C. Keck, Phys. Rev. **85**, 410 (1952).
[32] Kerst, Koester, Penfold, and Smith, Phys. Rev. **87**, 197 (1952).

from carbon are undetected when carbon is bombarded by 320-Mev bremsstrahlung. The corresponding figure for copper is 6 percent, and it is less for heavier elements.

The same data, together with those of Kikuchi[33] and the present experiment, can be used to estimate the yield of the $Cu^{63}(\gamma,n)Cu^{62}$ reaction due to quanta of energy greater than 24 Mev. The maximum error in beam monitoring from neglecting a possible high energy "tail" to this reaction is 3 percent. An experimental check on the Berkeley synchrotron in the region from 80 to 320 Mev showed that the ratio of neutron yields from deuterium to copper foil activity was consistent with assuming no tail to the $Cu^{63}(\gamma,n)Cu^{62}$ reaction.

The reaction $Cu^{65}(\gamma,3n)Cu^{62}$ would have the same effect on the monitor activity as such a tail, and it is estimated from the work of Strauch[34] on the reaction $Zn^{66}(\gamma,3n)Zn^{63}$, that the monitoring error can be as much as 3 percent from this source.

Because of these monitoring errors, the small cross sections over the range of 30 to 80 Mev might be low by amounts varying from 15 percent for the lowest $Z$ elements to 100 percent for the highest. In this region the cross sections may have additional errors of from 20 percent for the low $Z$ elements to 50 percent for the highest, because of the experimental errors in the yield points.

The relative areas under the low-energy peaks of the excitation functions are accurate to 10 percent, with the exception of those for Be, C, and Al which are accurate to 20 percent. The same accuracy applies to the areas under the cross-section curves from 80 to 320 Mev. The lower detection efficiency for high-energy neutrons has been neglected in these estimates. The actual curve shape in the low- and high-energy regions is probably good only to 30 percent. The absolute magnitude factor was mentioned in the previous section to be accurate to 15 percent.

## DISCUSSION

The shapes and magnitudes of the low-energy peaks agree very well with the $(\gamma,n)$ cross sections measured by other experimenters using induced activities. The decrease in total neutron cross sections following the peaks is not as fast as that of the $(\gamma,n)$ curves, indicating the presence of some competing reactions. The drop is sufficient, except in the case of beryllium, to indicate that the photon-absorption cross section has a resonance-like shape in the 20-Mev region.

The areas under the cross-section peaks to 27.5 Mev, plotted in Fig. 6, fit the equation

$$\int_0^{27.5} \sigma_n(E)dE = 5.2\times10^{-4}A^{1.8} \text{ Mev-barns.} \quad (6)$$

Beryllium is a factor of two above the curve, probably as a result of its loosely bound neutron. The integrated cross section predicted by the Levinger and Bethe[35] theory for electric dipole excitation is given by

$$\int_0^{\infty} \sigma_a(E)dE = 0.06\frac{NZ}{A}(1+0.8x) \text{ Mev-barns,} \quad (7)$$

where $x$ is the fraction of neutron-proton exchange force. The experimental increase in the integrated cross section with $A^{1.8}$ rather than $A$ is interpreted as being due to the neutron multiplicity, as Levinger and Bethe have pointed out.[36]

The curves show that the photon-absorption cross section is appreciable in the energy region from 25 to 100 Mev. This is also indicated by the work of others.[34,37]

To obtain a numerical value for the photon-absorption cross section from the neutron production cross section, the number of neutrons emitted must be known. Levinger and Bethe[36] have shown that above the $3n$ threshold the neutron multiplicity can be expressed as the ratio of the excitation energy $E$ to the average energy required to emit a neutron $E_b$, and they have calculated $E_b$ for five elements from copper to uranium. By drawing a smooth curve through their values and a value obtained for aluminum by assuming equal proton and neutron emission, $E_b$ was estimated for all targets in this experiment from aluminum to uranium. The photon-absorption cross sections at 45 Mev were calculated for these elements by dividing the total neutron cross section by the neutron multiplicity. The elements from Al to Ag fit the linear equation

$$\sigma_a(45) = 0.13A\times10^{-27} \text{ cm}^2, \quad (8)$$

while the four high $Z$ elements lie an average of about 30 percent below this line, well within the estimated error for this region due to error in the assumed monitor reaction cross section.

Levinger and Bethe have calculated the neutron multiplicity curve for $Ta^{181}$, a single isotope. The photon-absorption cross section curve for $Ta^{181}$ as shown in Fig. 7 was found by dividing the neutron production cross-section curve by their calculated neutron multiplicity. The photon-absorption cross section at low energy from a similar experiment by Whalin and Hanson[38] is shown on the same figure.

The area under the photon-absorption curve for $Ta^{181}$ can be compared with the Levinger and Bethe formula. Levinger and Bethe's theory gives 3.66 Mev-barns for an exchange force fraction one-half, and 4.70 Mev-barns for an exchange force fraction of unity. The experimental integrated cross section is 4.2 Mev-barns to 27.5 Mev and 5.1 Mev-barns to 80 Mev. The absolute accuracy is estimated to be 20 percent. The experimental values are somewhat higher than those predicted by theory.

[33] S. Kikuchi, Phys. Rev. **86**, 41 (1952).
[34] K. Strauch, Phys. Rev. **81**, 973 (1951).
[35] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).
[36] J. S. Levinger and H. A. Bethe, Phys. Rev. **85**, 577 (1952).
[37] N. Sugarman and R. Peters, Phys. Rev. **81**, 951 (1951).
[38] E. A. Whalin and A. O. Hanson, Phys. Rev. **89**, 324 (1953).

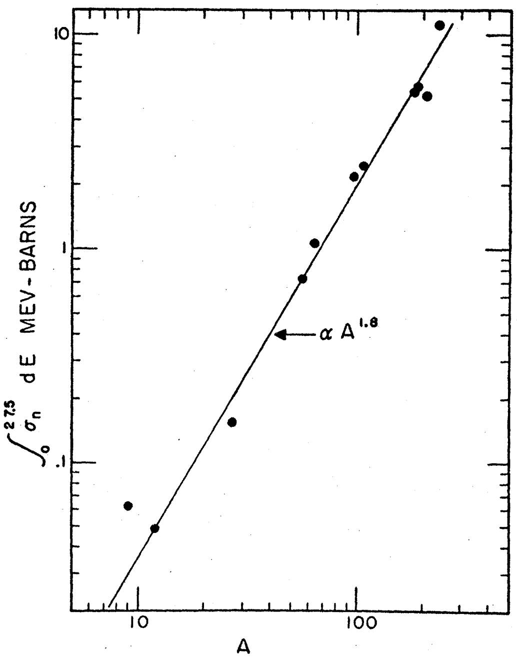


FIG. 6. Values of $\int_0^{27.5}\sigma_n(E)dE$, the integrated cross section for photoneutron production, as a function of atomic weight $A$.

Above about 80 Mev, most of the neutron production cross sections rise continuously to 320 Mev. The low $Z$ elements fail to do so probably because of the higher energy and limited multiplicity of the emitted neutrons. Levinger and Bethe calculate that it requires an average of 11 Mev to liberate each neutron from $Ta^{181}$ in the region where the statistical model applies, and only neutrons are emitted. At high-excitation energies this is obviously a lower limit. With the use of this figure, however, a lower limit of the photon-absorption cross section curve for $Ta^{181}$ can be obtained. This minimum photon-absorption cross section increases slightly from 80 to 320 Mev, the integrated cross section over that region being about 4 Mev-barns.

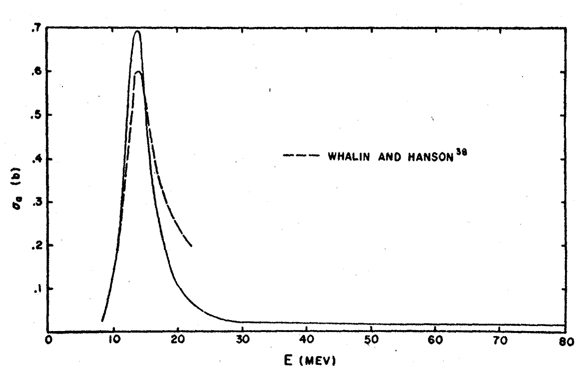


FIG. 7. Cross section for photonuclear absorption in tantalum $\sigma_a$ as a function of quantum energy $E$. Calculated from the excitation function for photoneutron production, with the use of the theoretical neutron multiplicity. Also shown are the results of Whalin and Hanson from a similar experiment.

The experimental results at low energy appear to account for the theoretical integrated cross section for electric dipole transitions, while the high-energy results must be due to the same photomesonic interactions responsible for stars, high-energy protons, and real meson production. The cross sections for star production from emulsion nuclei have been found by Miller[39] and Kikuchi[33] to be increasing functions of the photon energy, as is the cross section for photomeson production from hydrogen.[40] These cross sections increase more rapidly with photon energy than the minimum photon-absorption cross section for tantalum obtained in this experiment, but this is at least partially due to the increasing failure of the compound nucleus model at higher energies.

Recent Cornell experiments[41] on neutron production by meson absorption, which used a similar neutron detection system, give an indication of the neutron multiplicity for 140-Mev excitation. The results are given in Table I.

The multiplicity for lead is 30 percent lower than that for bismuth estimated from an extension of Levinger's

TABLE I. Photon-absorption cross sections at 140 Mev. $\sigma_n(150)$ is the cross section for total neutron production by 140-Mev quanta, $\nu(140)$ the neutron multiplicity obtained from $\pi^-$ absorption,[41] and $\sigma_a(140)$ the cross section for nuclear absorption of 140-Mev quanta.

| Element | C | Al | Ag | Pb |
|---|---|---|---|---|
| $\sigma_n(140)\times10^{-27}$ cm$^2$ | 1.2 | 5.4 | 80 | 278 |
| $\nu(140)$ | 1.6 | 2.0 | 6.1[a] | 9.3 |
| $\sigma_a(140)=\sigma_n/\nu\times10^{-27}$ cm$^2$ | 0.75 | 2.7 | 13 | 30 |
| $\sigma_a/A\times10^{-28}$ cm$^2$ | 0.62 | 1.0 | 1.2 | 1.4 |

[a] Value obtained for Sn.

simplified statistical model. With the use of these multiplicites, photoabsorption cross sections were obtained for those elements for 140-Mev quanta, with Sn being replaced by Ag. These cross sections may be approximately represented by the curve

$$\sigma_a(150)=0.32A^{1.3}\times10^{-28}\text{ cm}^2. \qquad (9)$$

The cross sections for photon absorption per nucleon at the meson threshold are comparable in magnitude to those for star production[39] and meson production from hydrogen and deuterium at 200 Mev.[40]

The theory of Huddlestone and Lepore[42] for photodisintegration of deuterium predicts an increase with energy in photon-absorption cross section below the meson threshold, because of photon interaction with the exchange currents. The values of $\sigma_n/E$ for Ta, W, Pb, and U all show such an increase from 80 to 150 Mev,

[39] R. D. Miller, Phys. Rev. 82, 260 (1951).
[40] K. A. Brueckner and K. M. Watson, Phys. Rev. 86, 923 (1952).
[41] V. Cocconi Tongiorgi and D. A. Edwards, Phys. Rev. 88, 145 (1952).
[42] R. H. Huddlestone and J. V. Lepore, Phys. Rev. 87, 207 (1952).

and presumably the cross sections for photon absorption increase at even a greater rate.

In the energy region from 50 Mev to the meson threshold, the photonuclear interaction may be a combination of photoelectric effect decreasing with energy and a photomesonic effect increasing with energy.

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# Collision Lengths of Neutral, Penetrating-Shower-Producing Cosmic Radiation in Light and Heavy Water*

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The collision length, $L_c$, of neutral penetrating-shower-producing cosmic radiation incident through a reinforced concrete roof of thickness 25 g/cm$^2$ at Los Alamos, New Mexico, altitude 2280 meters, was measured in light and heavy water. The values obtained were, for $H_2O$, $L_c=113\pm10$ g/cm$^2$ and for $D_2O$, $L_c=123\pm10$ g/cm$^2$. Equal masses of oxygen per unit area in the $H_2O$ and $D_2O$ absorbers were used for a determination of the difference between the collision cross sections of the deuteron and of the proton for the incident particles. The value obtained for this difference was $\sigma_D-\sigma_P=13\pm15$ mb.

## I. INTRODUCTION

DURING the past few years much attention has been given hard-shower production by both charged and neutral high-energy cosmic-ray particles. The general purpose of work in this field is to gain an understanding of high-energy nucleon-nucleus and nucleon-nucleon interactions involving, among other phenomena, $\pi$-meson production. One of the quantities frequently measured is the collision length, which may be defined as the mean thickness of material, measured in g/cm$^2$, through which an incident particle travels before it undergoes a nuclear interaction.

The collision length $L_c$ for a radiation which produces penetrating showers[1] is given by $L_c=(m/\sigma)$ g/cm$^2$, where, for a molecular substance, $m$ is the mass of a molecule of the substance and $\sigma$ is the sum of the effective collision cross sections for the production of penetrating showers in the nuclei composing the molecule.

It has been found that for materials of high atomic mass such as lead, the observed collision length agrees well with the calculated geometric collision length[2] $L_g=m/\sigma_g$. For materials of low atomic mass, the observed collision length is usually greater than the geometric, the difference sometimes being attributed to a "transparency" of nuclei. It is clear, however, that as the atomic number decreases the geometric collision length becomes less meaningful because it is based upon the concept of spherical nuclei of constant, uniform density.

The production of the $\pi$ mesons of a penetrating shower has been described by two different processes. The plural process, proposed by Heitler and Janossy[3] assumes that the incident particle produces one meson in each collision with a nucleon and that a shower of several mesons is built up through successive collisions with several different nucleons in the same nucleus. The multiple process, proposed by Heisenberg[4] and applied by Fermi[5] in statistical calculations of shower parameters, supposes that several mesons, and possibly some nucleons, are produced in an encounter of the incident particle with a single nucleon. Lewis[6] has summarized the present state of the theory of multiple meson production by collisions of nucleons.

It has now become fairly clear that the multiple process does occur in nature and that multiplications of a shower produced in a first collision with a nucleon can take place within the struck nucleus. Thus, the best description appears to be a kind of plural process

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[1] For a discussion of this subject and references to the literature, see Bruno Rossi, *High Energy Particles* (Prentice-Hall, Inc., New York, 1952).

[2] In this paper, $\sigma_g=\pi r_0^2 A^{2/3}$, where $A$ is the atomic mass number and $r_0=1.37\times10^{-13}$ cm.

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