Relative Photoneutron Yields from the 330-Mev Bremsstrahlung*

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Relative photoneutron yields were determined for 50 elements bombarded by the 330-Mev x-ray bremsstrahlung of the Berkeley synchrotron. The determinations were made at 90° to the beam axis with a paraffin moderated BF_3 proportional counter. Relative yields for elements above atomic number 30 were proportional to $Z^{1.7}$. Yields for low Z elements show a correlation with the binding energy of the last neutron. Angular distributions of photoneutrons were briefly investigated, and a Pb transition curve for photoneutrons was run.

PREVIOUS to July, 1950, workers at the General Electric laboratories had determined yields from some (γ,n), $(\gamma,2n)$, and (γ,np) reactions by studying the induced activities.[1] Kerst and Price[2] had studied relative neutron yields for over 50 elements from x-rays of the 22-Mev Illinois betatron by neutron counting. Strauch[3] had studied a few reactions by induced activities, and with transition curves had determined the reaction energies for these reactions, finding effective energies as high as 80 Mev.

In view of Strauch's findings, a comprehensive study was made of photoneutron yields from the 330-Mev x-ray bremsstrahlung by a direct neutron counting experiment. The experiment here described consisted of bombarding various elements with the x-ray beam of the synchrotron and counting the ejected photoneutrons in a direction 90° to the beam axis with a BF_3 proportional counter.

The counter was imbedded in a paraffin cylinder in order to moderate and count high energy neutrons. This long counter geometry is given in Rossi and Staub[4] as having a uniform response to neutrons of all energies to 5 Mev, and Kerst[5] mentions that his laboratory has estimated that a similar counter is 60 percent as efficient for 15-Mev neutrons as for low energies. An overhead view of the experimental arrangement is shown in Fig. 1. The beam was monitored by an ionization chamber, which was energy calibrated by Blocker and Kenney.[6] This calibration, in conjunction with a standard 500-mg radium beryllium neutron source, enabled reduction of the data to neutrons/(erg×moles/cm²). The targets consisted of plates and powders, the latter sometimes in compound form. The thickness of the targets was kept less than $\frac{1}{3}$ shower unit to keep the loss of counts due to beam degradation less than 4 percent. The targets were tipped to prevent the neutrons from having to traverse the entire target width before reaching the counter. Checks showed that when the plane of the target was on the axis of the counter, the yield was considerably reduced.

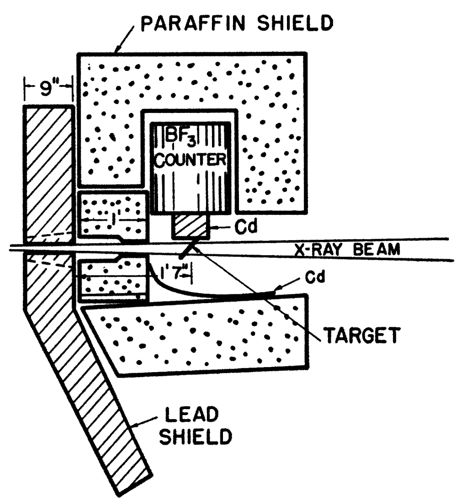

FIG. 1. Overhead view of the experimental arrangement. The x-ray beam originates in the synchrotron to the left of the lead shield.

Counting errors, including background, varied from 2 percent to 10 percent. Counts from background, which included the counts from the other elements of the targets in compound form, varied from 250 percent of the counts for vanadium (taken from $V_2O_2Cl_4$) to 4 percent of the counts for the metallic uranium target. The mean background was 20 percent of target counts. The total relative probable error varied from 4 percent to 12 percent with a mean of 6 percent.

The relative photoneutron yields of the elements *vs* Z (plotted in Fig. 2) show that the yield goes as $Z^{1.7}$ for Z greater than 30. U and Th lie high, owing to photofission neutron yields adding to the normal photoneutron yields. The points are in substantial agreement with those of Kerst obtained with the 320-Mev Illinois betatron.[7] The Illinois and Berkeley high energy data are both plotted in Fig. 3, with the Illinois data normalized to the Berkeley data at Pb. The normalization factor is 1.27. This 27 percent discrepancy is assumed to

* This work was performed under the auspices of the AEC.
[1] M. L. Perlman and G. Friedlander, Phys. Rev. **74**, 442 (1948). G. C. Baldwin and G. S. Klaiber, Phys. Rev. **73**, 1156 (1948). J. L. Lawson and M. L. Perlman, Phys. Rev. **74**, 1190 (1948).
[2] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).
[3] Karl Strauch, Phys. Rev. **81**, 973 (1951).
[4] B. Rossi and H. Staub, *Ionization Chambers and Counters* (McGraw-Hill Book Company, Inc., New York, 1949), pp. 196–197.
[5] D. W. Kerst, private communication.
[6] Blocker, Kenney, and Panofsky, Phys. Rev. **79**, 419 (1950).
[7] D. W. Kerst and G. A. Price, Phys. Rev. **79**, 725 (1950).

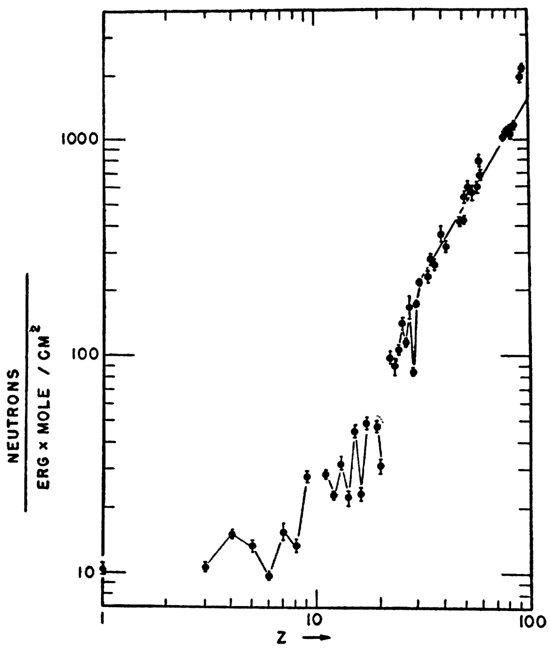

FIG. 2. Photoneutron yield in neutrons/(erg×moles/cm²) from 330-Mev bremmstrahlung plottted *vs* Z of the elements on a log log scale, showing relative errors. For $Z>30$ the yield goes as $Z^{1.7}$.

be due to beam energy and neutron source calibrations. Price and Kerst[7] and Baldwin and Elder[8] have reported a Z^2 yield at lower energies. For the low Z elements there is an even-odd alternation in yields. The low Z patterns for both the 22-Mev Illinois data and the 330-Mev Berkeley data are plotted in Fig. 3 and appear quite similar. This alternation is roughly related to the binding energy of the last neutron, as may be seen from the correlation plot of yield/A *vs* the binding energy of the last neutron in Fig. 4.

The yield in neutrons/(erg×moles/cm²) corresponds

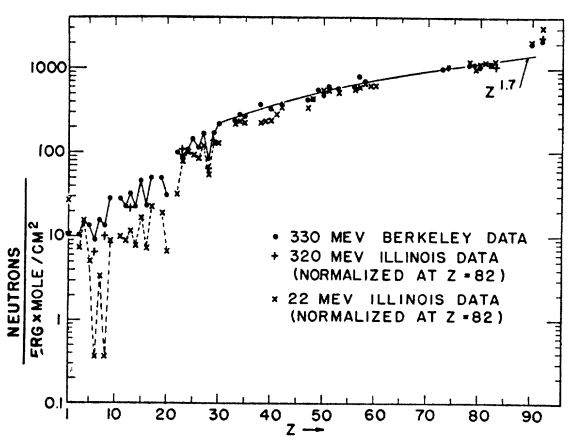

FIG. 3. Photoneutron yield in neutrons/(erg×moles/cm²) from 330-Mev bremmstrahlung plotted *vs* Z on a semilog graph, including data of Kerst and Price at 22 Mev and 320 Mev normalized to lead.

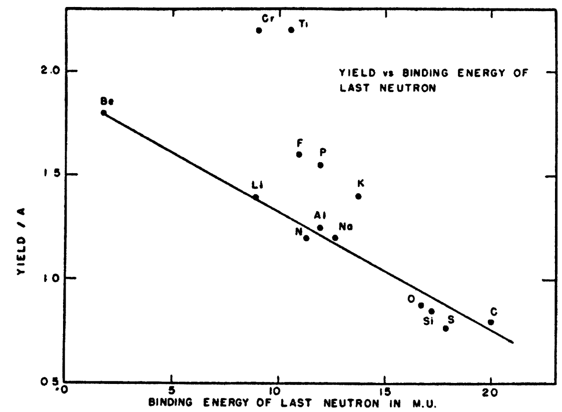

FIG. 4. Photoneutron yield/A *vs* the binding energy of the last neutron. Correlation with the binding energy of the last neutron is evident.

to $\int_0^{330} f(W)\sigma(W)dW$, where W is the photon energy, $\sigma(W)$ the photoneutron cross section at that energy, and $f(W)$ the number of photons of energy W in the beam. For a bremsstrahlung, $f(W)\sim 1/W$. The theory of Levinger and Bethe[9] would give a lower Z dependence of yield than the $Z^{1.7}$ dependence found experimentally.

A brief investigation was made into the angular distribution of the photoneutrons from D, C, S, Fe, Ni,

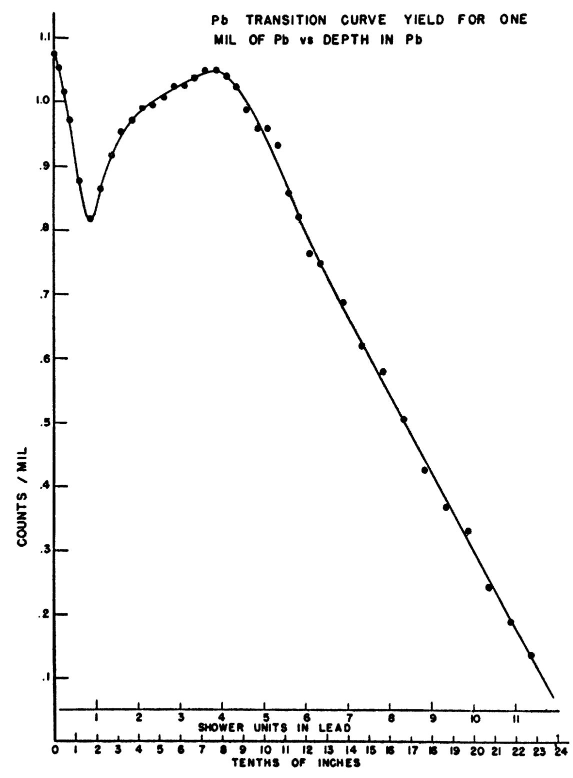

FIG. 5. Transition curve of photoneutrons from lead. The ordinate is the photoneutron yield from a unit thickness of lead placed behind the abscissa thickness of lead. The units of the ordinate are arbitrary.

[8] G. C. Baldwin and F. R. Elder, Phys. Rev. **78**, 76 (1950).

[9] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).

and Cu. Data were taken at 38°, 90°, and 142° to the beam axis. These targets were cylindrical to minimize asymmetrical neutron scattering in the target. Of the elements investigated, the photoneutrons were given off with spherical symmetry except for deuterium, carbon, and sulfur. The yield from carbon was down 10 percent at 38° and 142° from what it was at 90°, and from sulfur down 5 percent at the extreme angles. The deuterium results agree, within counting statistics, with the angular distribution reported by Kerst at 22 Mev. Some slight increase in yields was seen at small angles (38°) for some targets, but this appeared to be due to x-rays scattered by the target sample producing neutrons in the counter itself. Counting errors on deuterium ran as high as 25 percent, the others considerably lower.

A Pb transition curve was obtained by determining the yields from lead targets of varying thicknesses. The data were analyzed to give the transition curve shown in Fig. 5. The ordinate corresponds to the neutron yield a unit thickness of lead would give when placed behind the abscissa thickness of lead. There is an error introduced into the curve at larger thicknesses because of the lateral spreading of the shower and the finite diameter of the target. The initial sharp descent found by Strauch[3] to correspond to an 80-Mev process is seen; but this is followed by a broad rise peaked at about 4 shower units, which apparently indicates the usual type of (γ,n) resonance at 15–20 Mev.

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Production of Protons by High Energy γ-Rays*

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The protons ejected from various nuclei by the gamma-ray beam of the 320-Mev Berkeley synchrotron have been studied with a proportional counter telescope system. The energy distribution of the protons from carbon, copper, and lead from 7 Mev to 70 Mev at 90° was roughly proportional to $1/E^2$. The angular distribution was spherically symmetrical for 10-Mev protons and showed a pronounced forward maximum for protons of about 40 Mev. The cross section per nucleus for the ejection of 40-Mev protons was found to be proportional to Z.

The experimental results indicate that protons above 30 Mev arise primarily from the interaction of the γ-ray with some small subunit of the nucleus rather than through the formation of an excited compound nucleus.

I. INTRODUCTION

Since Chadwick and Goldhaber[1] demonstrated the photodisintegration of the deuteron in 1935, much work has been devoted to the study of γ-ray induced nuclear reactions. Studies have been made using various target nuclei bombarded with γ-rays from several radioactive sources[2] and from the $Li^7(p,\gamma)Be^8$ reaction.[3,4] Recently, the work has been extended to the high energy regions using the γ-ray beams from the high energy electron accelerators.[5,6] Most of the experiments have been studies of the radioactive end products of the reactions, so that total cross sections as a function of γ-ray energy and target nucleus have been obtained. This has led to rather conflicting evidence about the mechanism for inducing these reactions. For example, it seems difficult to reconcile the ratio of (γ,p) to (γ,n) cross sections[3,6] with an evaporation process unless one supposes a rather special character for the transitions allowed by γ-rays.[7] However, the resonances found for the reactions at about 20 Mev[5,6] can be understood as the excitation of nuclear dipole oscillations with the

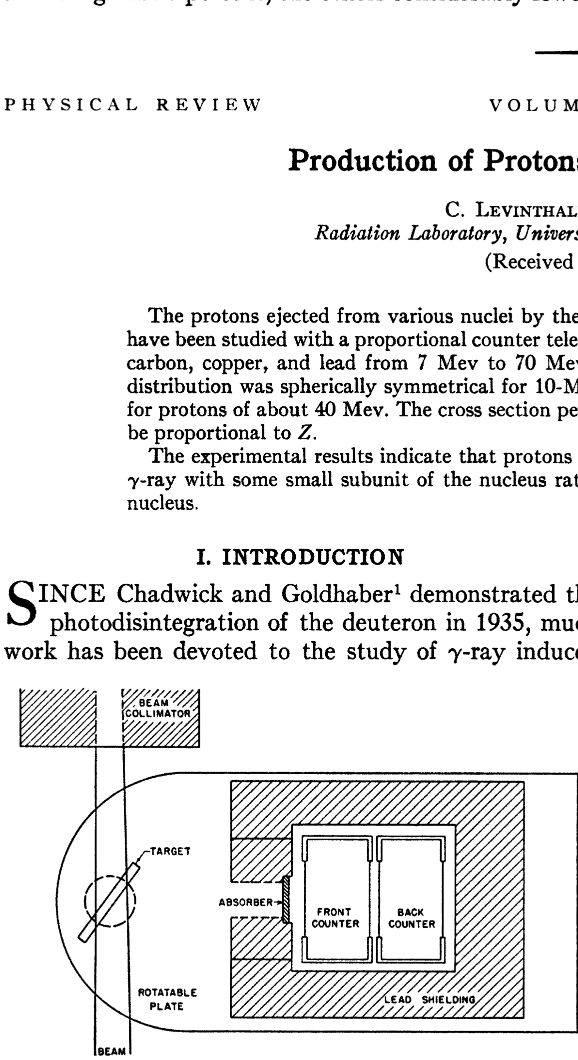

Fig. 1. Geometry of apparatus.

* This work was performed under the auspices of the AEC.
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