PHYSICAL REVIEW VOLUME 91, NUMBER 6 SEPTEMBER 15, 1953

Gamma Rays from Interaction of 14-Mev Neutrons with Various Materials

V. E. SCHERRER, R. B. THEUS, and W. R. FAUST
Naval Research Laboratory, Washington, D. C.
(Received April 23, 1953)

Experiments have been performed to observe the pulse-height distribution produced in a single crystal spectrometer by gamma radiation arising from bombardment of various materials with 14-Mev neutrons. Various gamma-ray lines have been identified and estimates made of the total cross section for gamma-ray production.

IN a previous paper,[1] we described some observations of gamma radiation produced by interaction of 14-Mev neutrons with iron. Further results of such experiments are given herein for several elements ranging in atomic weight from carbon to lead.

The experimental apparatus and techniques used were similar to those described in I. Briefly, 14.2-Mev neutrons from the $T^3(d,n)He^4$ reaction bombarded a converter arranged so that whenever a neutron entered the converter the corresponding alpha particle entered the accelerator monitor. The pulse-height distribution from converter gamma rays was observed by a scintillation spectrometer consisting of a single crystal of NaI(Tl) and a twenty-channel pulse-height analyzer. Coincidences between crystal and alpha monitor pulses were used to gate the pulse-height analyzer so that only reactions produced in the converter by neutrons were observed.

Experiments have been performed as described in I to observe pulse-height distributions for carbon, oxygen, aluminum, nickel, copper, cadmium, and lead. Pulse-height distributions were taken with the appropriate converter "in" and "out" of the coincidence neutron beam to obtain source and background data. Generally the source to background ratio was ten to one or greater with the exception noted later. The net counting data, obtained by subtraction of source and background observations are plotted in the accompanying figures in counts per Mev per incident neutron, as a function of secondary electron energy.

Energy calibration of the spectrometer was made as described in I. Gamma-ray energies were estimated directly from this data where available. In the region where pair production is comparable to the Compton process, the gamma-ray energy is 1.02 Mev above the corresponding electron energy, due to the loss of the two 0.51-Mev annihilation quanta.

There appears to be evidence of line or band spectra as indicated by maxima in the pulse-height distribution for all but one of the elements examined. The distributions were analyzed as arising from a continuous gamma-ray spectrum, superimposed upon a line spectrum. We give the results of such analysis by quoting the total gamma-ray production cross section and the cross section for each obvious line.

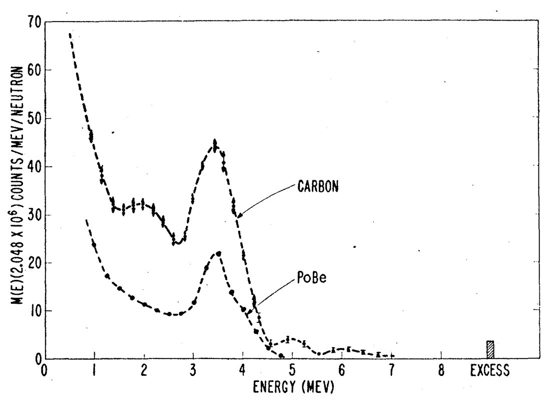

FIG. 1. Pulse-height distribution obtained from carbon and Po-Be gamma rays. Ordinates are counts per Mev per neutron for the carbon curve and counts per sec per Mev for the Po-Be curve.

CARBON

The pulse-height distribution for a carbon converter is given in Fig. 1 in counts per Mev per incident neutron. For comparison, the pulse-height distribution in counts per second per Mev obtained from a Po-Be source is also plotted. The similarity of these curves is due to the condition that the residual excited nucleus is C^{12} in both reactions. The 4.45-Mev gamma ray,[2]

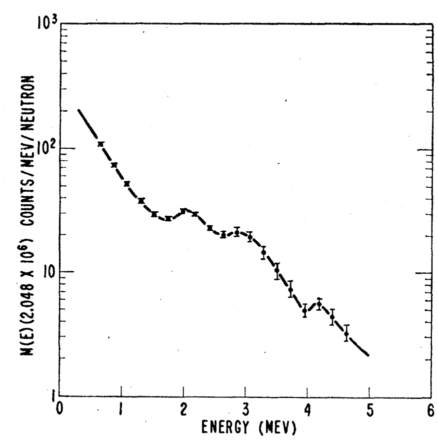

FIG. 2. Pulse-height distribution obtained from oxygen gamma rays.

[1] V. E. Scherrer *et al.*, Phys. Rev. **89**, 1268 (1953); hereafter referred to as I.

[2] J. Terrell, Phys. Rev. **80**, 1076 (1950).

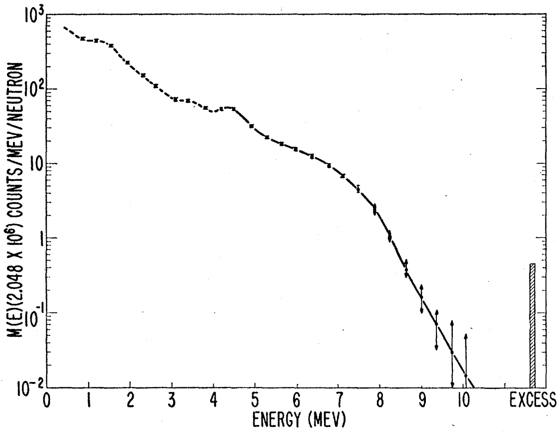

FIG. 3. Pulse-height distribution obtained from aluminum gamma rays.

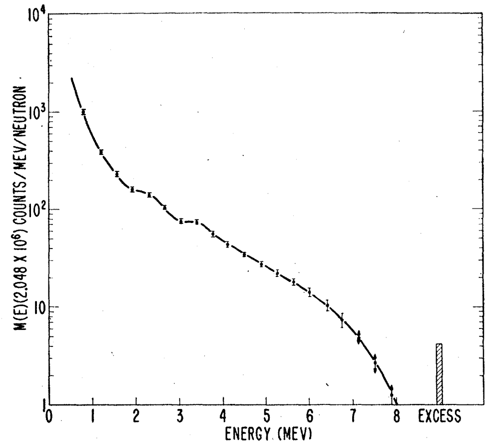

FIG. 5. Pulse-height distribution obtained from copper gamma rays.

which appears at a secondary electron energy of 3.43 Mev due to the loss of the two 0.51-Mev annihilation quanta, is quite evident in both cases. Differences between the curves are probably due to the higher excitation produced by 14-Mev neutrons on carbon as compared with the excitation of the residual nucleus in the reaction $Be^9(\alpha,n)C^{12}$.

An analysis of this pulse-height distribution, following the procedures outlined in I, indicates gamma rays at 2.8, 4.45, 6.0, and 7.0 Mev. The cross section for each line is 0.036, 0.069, 0.002, 0.002 barn, respectively, and the total cross section for gamma-ray production is estimated to be 0.19 barn.

OXYGEN

In these experiments, liquid oxygen in a vacuum flask was placed in the "coincidence neutron beam." Pulse-height distributions were taken both with the flask full and empty to obtain "source" and "background" data. The resulting source to background ratio was of the order of three to one. The pulse-height distribution so obtained is given in Fig. 2. Here there appear to be lines, at 3.0, 3.8, and 5.2 Mev having production cross sections of 0.086, 0.130, and 0.056 barn, respectively. The total cross section for gamma production is estimated to be 0.52 barn.

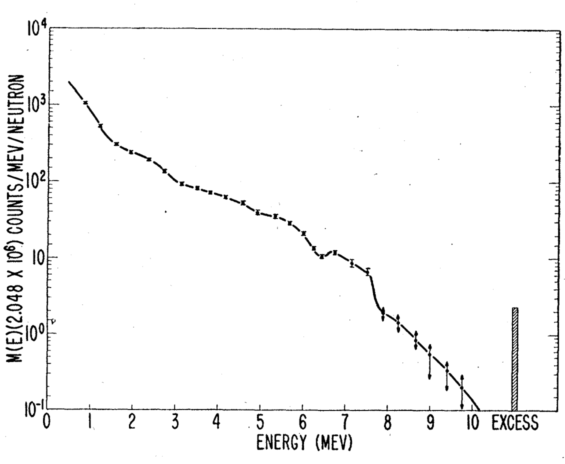

FIG. 4. Pulse-height distribution obtained from nickel gamma rays.

ALUMINUM

The pulse-height distribution obtained from aluminum is given in Fig. 3, from which it appears that there are maxima at electron energies of 1.5, 3.5, and 4.4 Mev. An analysis of this pulse-height distribution indicates that the production cross section is 1.7 barns while the cross sections are 0.176, 0.024, and 0.054 barn for the 1.7-, 4.5-, and 5.4-Mev gamma rays, respectively. A cross section of 0.0003 barn is estimated for the region above 11 Mev.

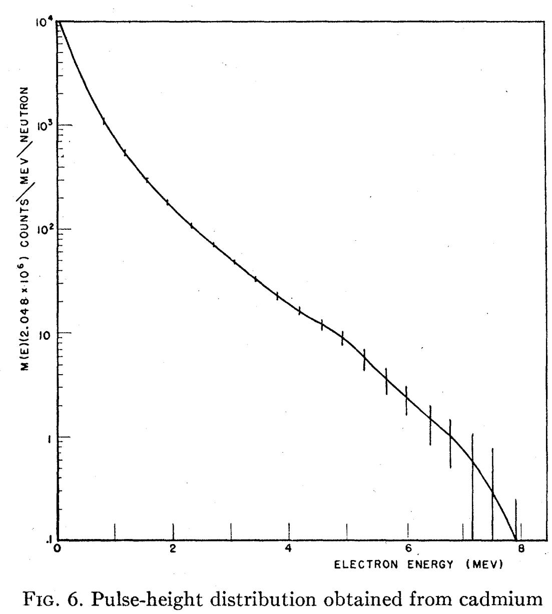

FIG. 6. Pulse-height distribution obtained from cadmium gamma rays.

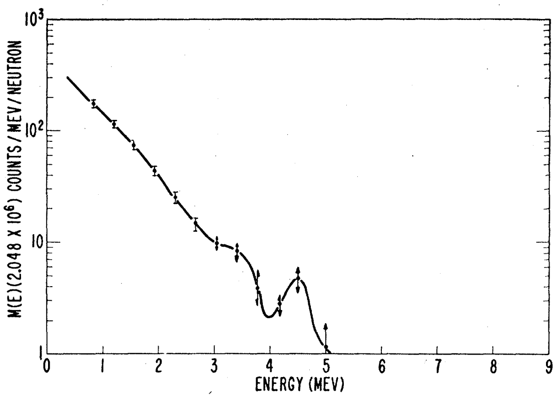

FIG. 7. Pulse-height distribution obtained from lead gamma rays.

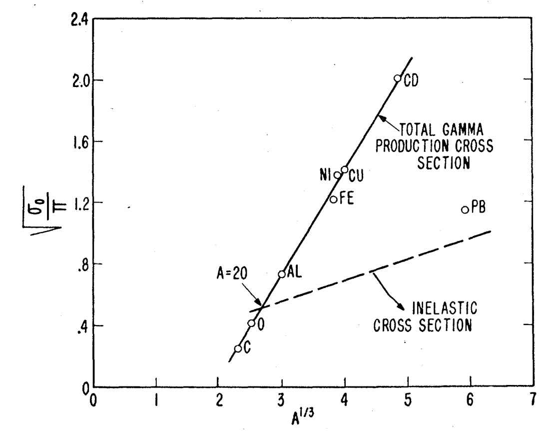

FIG. 8. Gamma-ray production cross section (barns) shown as a function of atomic mass.

NICKEL

The pulse-height distribution for nickel is given in Fig. 4 for which the total cross section is 6 barns. Lines at gamma-ray energies of 2.9, 5.2 Mev, 6.6 Mev, and 8 Mev have cross sections of 0.096, 0.021, 0.032, and 0.01 barn, respectively.

COPPER

A copper converter produced the pulse-height distribution given in Fig. 5. The total cross section for copper is computed as 6.3 barns and the apparent lines at 3.1 and 4.5 Mev have production cross sections of 0.052 and 0.029 barn, respectively. A cross section of 0.007 barn is estimated for the region above 8 Mev.

CADMIUM

The cadmium pulse-height distribution is given in Fig. 6. The total cross section for gamma-ray production is 12.8 barns. There appears to be no definite line structure present, however there appears to be a change of slope at an electron energy of about 4.5 Mev which corresponds to a gamma-ray energy of 5.5 Mev.

LEAD

The lead pulse-height distribution in Fig. 7 indicates two gamma rays in the distribution. It is found that the total cross section for gamma-ray production is about 4.2 barns while the lines at 4.4 Mev and 5.5 Mev have cross sections of 0.048 and 0.017 barn, respectively.

DISCUSSION

Probable errors in the counting data are represented by the vertical lines on the various pulse-height distributions. There are, however, other sources of error present in the cross-section computations that are more serious than the counting statistics. These errors arise from uncertainties in the absorption and scattering of neutrons and gamma rays in the converter and crystal as well as a lack of knowledge of the precise response of the spectrometer at all energies. It is estimated that the probable error in the total production cross section is about ± 25 percent while that associated with the lines is about ± 35 percent.

Gamma-ray production cross sections σ_0 are summarized in Fig. 8 where $(\sigma_0/\pi)^{\frac{1}{2}}$ is plotted against $A^{\frac{1}{3}}$, in which A is the total number of particles in the nucleus. Iron data from I is also included in this curve. For comparison, the inelastic cross section given by Phillips[3] is plotted in the same figure. It is somewhat unexpected that the gamma-ray cross section can be so simply represented. It is presumed that in the case of lead $(n,2n)$ reactions reduce the energy available for gamma-ray production so that the cross section falls below the value expected from extrapolating the curve. Both carbon and oxygen, on the other hand, have gamma-ray production cross sections below the inelastic cross section. Here it is possible that charged particle emission will occur and reduce the energy available for gamma-ray production.

The authors wish to thank Dr. E. H. Krause for his active interest and support, and express their appreciation to Messrs. A. P. Flanick and B. A. Allison for aid in performing the experiments.

[3] D. D. Phillips *et al.*, Phys. Rev. **88**, 600 (1952).