Gamma Radiation from Interaction of 3.2-Mev Neutrons with Various Materials

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(Received June 21, 1954)

Gamma radiation arising from 3.2-Mev neutron bombardment of 30 elements has been observed and calculations made of the gamma-ray production cross section for 15 of these elements.

A DETAILED investigation of gamma radiation arising from 3.2-Mev neutron bombardment has been made of thirty elements picked more or less uniformly from the periodic table. Calculations have been completed of the gamma-ray production cross sections for half of the elements examined. Some of the gamma rays reported have been observed in similar experiments,[1–3] although most of the data is essentially new. Gamma radiation observed is consistent with level information where available.

Use of a 12.7-cm diameter by 5.1-cm thick crystal of NaI(Tl) as a detector simplified analysis of the complex pulse-height distributions. Because of the large dimensions of the crystal, a large fraction of the secondary radiation is absorbed, thereby augmenting the photopeak.

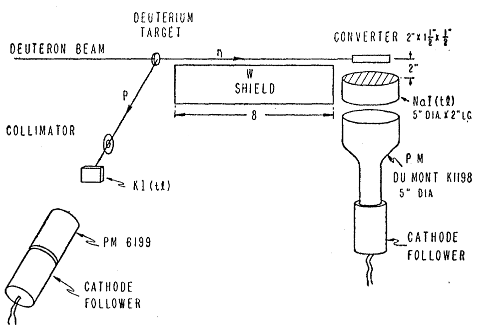

Fig. 1. Basic geometry of the experiment.

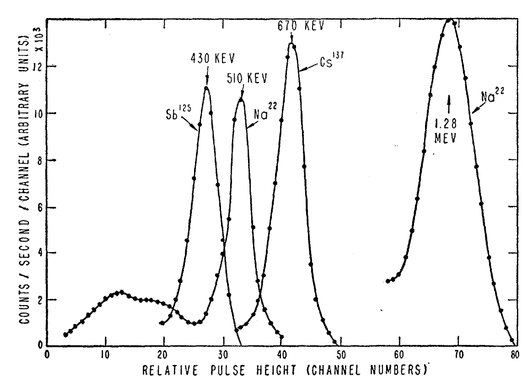

Fig. 2. Spectrometer calibration curves.

DESCRIPTION OF EXPERIMENTS

Neutrons were obtained from the D(d,n)He[3] reaction produced in a Cockcroft-Walton accelerator operated at 350 kv. The target was formed by adsorption of deuterium on aluminum and a KI(Tl) scintillation detector served as a monitor by counting protons from the D(d,p)T companion reaction. A converter, made of the material of interest, was placed about 25 cm from the accelerator target and in line with the deuteron beam as shown in Fig. 1. Estimates of the neutron energy distribution were made by a method described previously[4] which indicated that the neutrons were distributed asymmetrically about the average energy of 3.2 Mev and that the width of the distribution at half-maximum was 0.2 Mev. The spectrometer was placed 2.5 cm below the converter and was shielded from the target by a tungsten bar. Counting data was taken first with the converter in position and then with it removed. The difference between these two conditions yielded net counting data due to the presence of the converter.

The spectrometer consisted of a 12.7-cm diameter by 5.1-cm thick crystal of NaI(Tl) mounted on a DuMont K-1198 photomultiplier tube. Pulse-height distributions were recorded on a twenty-channel analyzer. Typical calibration curves of this spectrometer, which were obtained with extended sources placed in the converter position, are shown in Fig. 2.

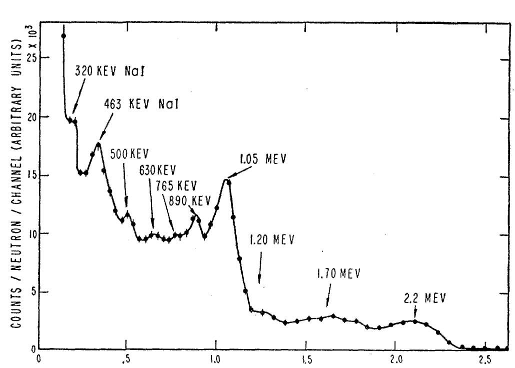

Fig. 3. Pulse-height distribution produced by 3.2-Mev neutron bombardment of Al.

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[2] R. M. Kiehn and C. Goodman, Phys. Rev. **93**, 177 (1954).
[3] Scherrer, Allison, and Faust, Phys. Rev. **95**, 637 (1954).
[4] Shapiro, Scherrer, Allison, and Faust, Phys. Rev. **95**, 751 (1954).

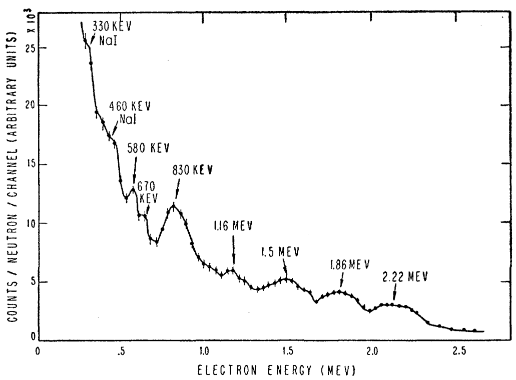

FIG. 4. Pulse-height distribution produced by 3.2-Mev neutron bombardment of Mn.

RESULTS

Pulse-height distributions obtained from Al, Mn, Zr, I, and Bi are shown in Figs. 3 through 7 and are typical of the general results. Data taken with a NaI(Tl) converter showed maxima near 210 kev, 330 kev, 420 kev, and 1.04 Mev, a distribution similar to the iodine distribution of Fig. 6. Maxima that occur at energies near the NaI(Tl) lines in the various figures probably arise from the interaction of scattered neutrons with the NaI(Tl) spectrometer crystal.

TABLE I. Gamma-ray production cross sections.

Element	Energy (Mev)	Cross section (Barns)	Element	Energy (Mev)	Cross section (Barns)
Cr	0.75 ±0.03	0.027	Mo	2.5 ±0.2	0.059
	0.97 ±0.04	0.10		1.4 ±0.06	0.33
	1.43 ±0.06	0.73		0.73±0.03	0.66
				plus unresolved lines	
Fe	0.835±0.015	1.18			
	1.17 ±0.05	0.39	Cd	0.57±0.02	0.69
	1.67 ±0.07	0.33		2.8 ±0.2	0.016
				plus unresolved lines	
Co	0.60 ±0.02	0.20		0.77±0.03	0.16
	1.15 ±0.04	0.82	In	0.88±0.04	0.27
	1.49 ±0.07	0.53			
	1.7 ±0.08	0.15		2.08±0.1	0.16
	2.5 ±0.1	0.19		1.15±0.05	0.10
Ni	0.59 ±0.02	0.047	Sn	0.69±0.02	0.14
	1.33 ±0.05	0.84		1.14±0.05	1.67
	1.49 ±0.06	0.54		2.0 ±0.1	0.21
	2.66 ±0.1	0.01			
Cu	0.66 ±0.03	0.21	Ta	0.46±0.03	1.26
	0.96 ±0.05	0.12		1.44±0.15	0.93
	1.37 ±0.06	0.81			
	1.9 ±0.1	0.16		plus unresolved lines	
			Pb	0.35±0.02	0.52
Zn	1.02 ±0.05	1.3		0.52±0.02	1.02
	1.3 ±0.06	0.03		0.80±0.03	1.05
	1.6 ±0.07	0.02		1.10±0.05	0.18
				1.40±0.10	0.25
Zr	0.690±0.04	0.038		2.20±0.10	0.16
	0.893±0.04	0.402			
	1.14 ±0.06	0.12	Bi	0.49±0.02	0.43
	1.5 ±0.07	0.14		0.94±0.05	1.2
	2.17 ±0.1	0.44		1.62±0.07	0.59
				2.6 ±0.1	0.37

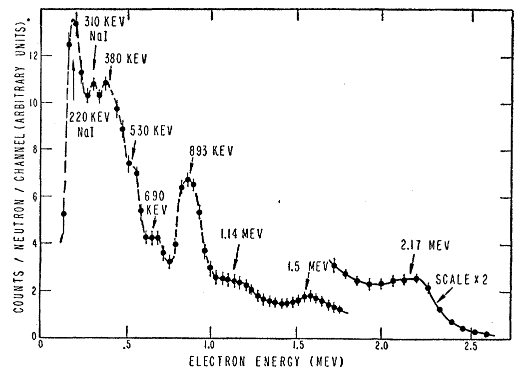

FIG. 5. Pulse-height distribution produced by 3.2-Mev neutron bombardment of Zr.

Table I lists gamma rays definitely identified in the spectrum of each element examined. Also listed is the

TABLE II. Identified gamma rays for which no calculations have yet been made of corresponding production cross sections.

Element	Gamma-ray energy (Mev)	Element	Gamma-ray energy (Mev)
Be	none	Nb	0.27 ±0.02
			0.53 ±0.02
B	0.43[a]±0.02		0.69 ±0.03
	0.76 ±0.03		0.91 ±0.05
	1.02 ±0.05		
	1.17 ±0.05	Ag	0.74 ±0.03
	1.41 ±0.06		1.10 ±0.05
	1.61 ±0.08		1.50 ±0.06
	2.00 ±0.18		
		Te	0.72 ±0.04
C	none		1.10 ±0.05
			1.43 ±0.06
Mg	0.38 ±0.02		2.30 ±0.18
	0.59 ±0.02		
	1.30[a]±0.05	I	0.21 ±0.01
	1.79 ±0.08		0.33 ±0.01
			0.42[a]±0.02
Al	0.05 ±0.02		0.63[a]±0.03
	0.89 ±0.03		1.04 ±0.05
	1.05 ±0.05		
	1.20 ±0.05	Ba	0.47[a]±0.02
	1.70 ±0.08		0.60 ±0.03
	2.20 ±0.18		0.78 ±0.04
			1.06 ±0.05
P	1.0 ±0.05		1.19 ±0.05
	1.24[a]±0.05		1.41[a]±0.06
	1.60 ±0.07		1.51 ±0.06
	1.75 ±0.08		2.10 ±0.1
	2.05 ±0.18		
		Ce	0.48 ±0.03
Ti	0.92[a]±0.05		0.90 ±0.05
	1.30 ±0.06		1.50 ±0.06
	2.2 ±0.18		2.50 ±0.20
V	0.33[a]±0.02	Hg	0.38[a]±0.02
	0.97 ±0.05		0.54 ±0.03
	1.67 ±0.07		0.90 ±0.05
			1.21 ±0.05
Mn	0.58 ±0.02		2.0 ±0.18
	0.67 ±0.03		
	0.83[a]±0.04		
	1.16 ±0.05		
	1.50 ±0.06		
	1.86[a]±0.08		
	2.22[a]±0.17		

[a] Indicates strong lines.

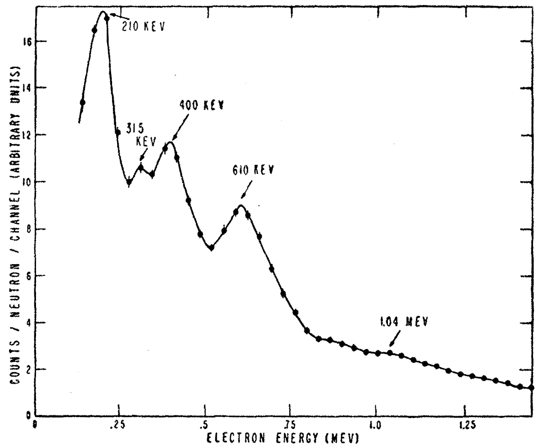

FIG. 6. Pulse-height distribution produced by 3.2-Mev neutron bombardment of I.

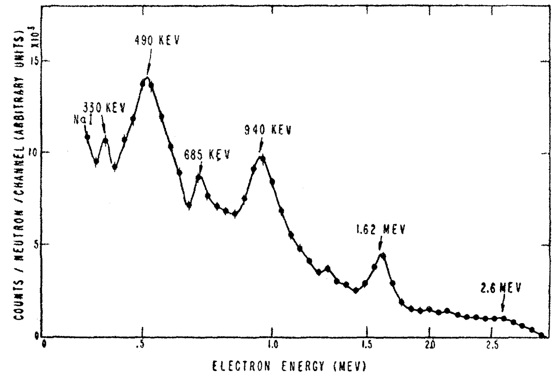

FIG. 7. Pulse-height distribution produced by 3.2-Mev neutron bombardment of Bi.

cross section σ_γ for the production of a gamma ray of that particular energy. These cross sections were obtained by measuring the total number of counts per neutron under each photoabsorption peak and correcting for attenuation of both neutrons and gamma rays in the converter. Some auxiliary experiments with carbon converters, similar to those described by Rothman and Mandeville,[1] indicated that the contribution to the area under the photopeaks from the NaI background was generally small. Absolute calibrations of the detector was carried out by placing extended sources of known energy and disintegration rate at the converter position. Calibration data similar to those of Fig. 2 indicated the number of photons in the photoabsorption peaks as a function of gamma-ray energy. It is estimated that the average error in the cross section calculation is ± 20 percent.

Table II lists gamma rays identified in the spectrum of elements for which no calculations have yet been made of the corresponding production cross sections.

ACKNOWLEDGMENT

The authors wish to express their appreciation to Dr. P. Shapiro and Dr. C. V. Strain for their active interest and support and to thank Mr. A. P. Flanick for invaluable aid given during the course of the experiments.