PHYSICAL REVIEW VOLUME 110, NUMBER 6 JUNE 15, 1958

Photoneutron Thresholds for Iron, Germanium, Rubidium, and Hafnium

R. TOBIN, J. MCELHINNEY, AND L. COHEN
Nucleonics Division, United States Naval Research Laboratory, Washington, D. C.

(Received February 27, 1958)

Photoneutron thresholds for Fe^{56}, Fe^{57}, Ge^{73}, Rb^{85}, Rb^{87}, Hf^{177}, and Hf^{179} have been measured by using bremsstrahlung from a 22-Mev betatron as a photon source. The photon-induced reactions were observed by neutron detection supplemented in one case by radioactivity determinations.

A comparison of these thresholds with neutron binding energies revealed that, for some of the nuclei, better agreement was obtained if formation of the residual nucleus in an excited state instead of in the ground state was assumed. The neutron binding energies inferred from these measurements are: 11.34 ± 0.10 Mev for Fe^{56}; 7.85 ± 0.13 Mev for Fe^{57}; 6.50 ± 0.16 Mev for Ge^{73}; 10.50 ± 0.08 Mev for Rb^{85}; 9.89 ± 0.05 Mev for Rb^{87}; 6.70 ± 0.09 Mev for Hf^{177}; and 6.52 ± 0.12 for Hf^{179}.

I. INTRODUCTION

THE binding energy of a neutron in a nucleus is intimately associated with the observed threshold energy for a (γ,n) reaction. If conditions are favorable for the (γ,n) reaction to take place close to the theoretical threshold energy (i.e., with very low neutron energy and no excitation of the residual nucleus), then the observed threshold can be identified directly with the neutron binding energy. If, however, the reaction is inhibited close to the theoretical threshold, the observed threshold may be associated with excited levels of the residual nucleus, or it may represent only an upper limit to the binding energy.

Described herein are several thresholds measured by detection of the emitted neutrons and one by detection of the delayed gamma rays from an isomeric state. Some of these results were described at the American Physical Society Meeting in Chicago, 1956.[1]

II. EXPERIMENTAL TECHNIQUE

The general experimental setup used for detecting the neutrons was similar to that of Sher, Halpern, and Mann,[2] and is shown in Fig. 1. X-rays from the 22-Mev NRL betatron were monitored with the aid of a transmission ionization chamber having thin aluminum walls. A tapered hole in an 8-in. lead wall limited the beam to about $1\frac{1}{2}$ in. in diameter at the sample position, 93 in. from the betatron target. The photoneutrons emanating from the sample were detected by eight General Electric B^{10}-lined proportional counters, embedded in a paraffin block, and placed around the sample. A 3-ft-thick concrete wall with a hole for the beam was built in front of the betatron and a 0.040-in. cadmium jacket surrounded with extra paraffin was placed around the paraffin block in order to shield the counters from neutrons originating in the betatron and in the lead collimator.

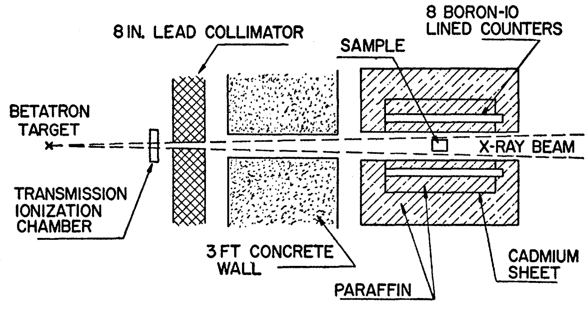

FIG. 1. Schematic diagram showing the experimental arrangement for detecting photoneutrons.

The photoneutrons produced in the sample during the $\frac{1}{4}$-microsecond x-ray burst were moderated in the paraffin, and detected somewhat later in the B^{10} counters. The counting rate following each x-ray pulse was roughly exponential in time with about a 180-micro-

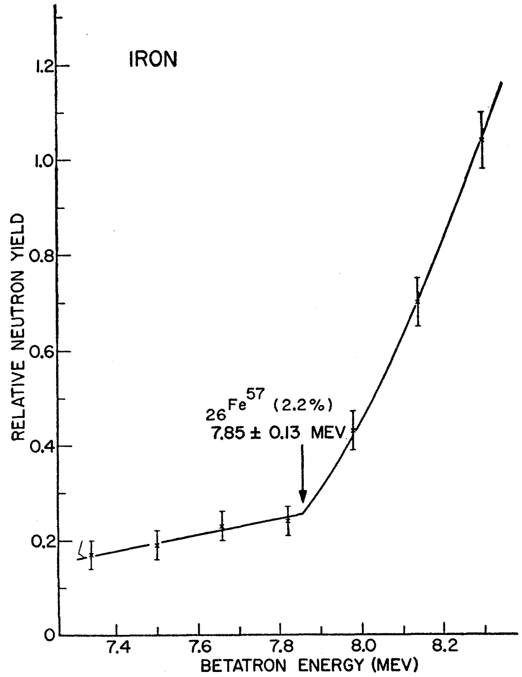

FIG. 2. Photoneutron yield from iron in the betatron-energy range from 7.3 to 8.3 Mev.

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[1] R. Tobin and J. McElhinney, Bull. Am. Phys. Soc. Ser. II, 1, 340 (1956).

[2] Sher, Halpern, and Mann, Phys. Rev. 84, 387 (1951).

TABLE I. Summary of observed thresholds.

Element	Mass number	Isotopic abundance (percentage)	Expected neutron binding energy (Mev)	Reference	Neutron binding energy inferred from this experiment (Mev)
Iron	54	5.9	13.2 ±0.1	6	
	56	91.6	11.18±0.04	6	11.34±0.10
	57	2.2	7.64±0.01	6	7.85±0.13
	58	0.33	10.10±0.01	6	
Germanium	70	20.5	11.56±0.08	6	
	72	27.4	11.3 ±0.1	6	
	73	7.8	6.4 ±0.1	6	6.50±0.16
	74	36.5	10.14±0.07	6	
	76	7.8	9.6 ±0.4	6	
Rubidium	85	72.2	10.26±0.07	6	10.50±0.08
	87	27.8	9.91±0.01	6	9.89±0.05
Hafnium	174	0.18	8.23	12	
	176	5.2	7.92	12	
	177	18.5	6.38	12	6.70±0.09
	178	27.1	7.61	12	
	179	13.8	6.09	12	6.52±0.12
	180	35.2	7.31	12	

second half-life. To permit the counters to recover from the x-ray bursts and to avoid excess counts from the random background, the circuits were gated so that neutrons were detected only during the interval from 30 to 730 microseconds following each x-ray burst.

The induced radioactivity was utilized in measuring one of the photoneutron thresholds for rubidium. Details are discussed below.

III. RESULTS AND DISCUSSION

Data are presented in the form of "relative neutron yield" or "relative activity" as a function of "betatron energy". "Betatron energy" is the maximum photon energy in the bremsstrahlung beam. The energy calibration of the betatron was derived from observations of the photoneutron thresholds of deuterium, fluorine, and oxygen, with values of 2.228, 10.416, and 15.658 Mev, respectively, being assigned to them. These values represent the thresholds expected in the laboratory system based on mass data of Wapstra[3] and on a recent measurement of the O^{15} positron energy by Kistner *et al.*[4] A check with the (γ,n) threshold for nitrogen showed very good agreement.[5]

The uncertainties assigned to the observed thresholds take into account the counting statistics at each point and the corresponding uncertainties in the calibration thresholds.

A. Iron

The iron sample consisted of a block of commercially pure steel weighing 611 grams. The effective mass was smaller than this because of the beam collimation and the x-ray and neutron absorption by the sample. Figure 2 shows the relative neutron yield in the vicinity of the lowest threshold. This yield, which begins to increase rapidly at 7.85±0.13 Mev, is attributed to the $Fe^{57}(\gamma,n)Fe^{56}$ reaction on the basis of a comparison with neutron binding energies listed by Way *et al.*,[6] and is shown in Table I. The observed threshold appears slightly higher than any of the reference values chosen by Way *et al.* and should be considered an upper limit to the binding energy. The discrepancy is not large enough to involve any known excited level of Fe^{56}. The observed threshold is in agreement with the value of 7.75±0.20 Mev reported by Sher *et al.*,[2] even though their analysis was based on data considerably removed from threshold and on the assumption of a power-law behavior to determine threshold.

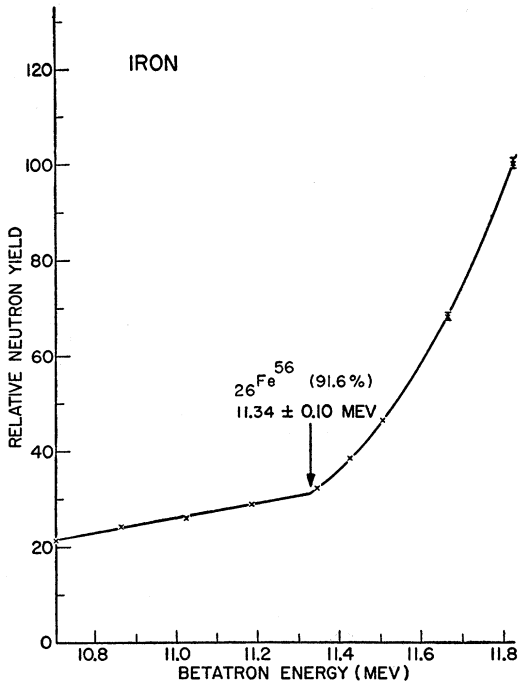

FIG. 3. Photoneutron yield from iron in the betatron-energy range from 10.7 to 11.8 Mev.

The next break to appear in the photoneutron yield as the betatron energy was increased is shown in Fig. 3. The assigned energy, 11.34±0.10 Mev, is attributed to the $Fe^{56}(\gamma,n)Fe^{55}$ reaction because of the high relative abundance of that isotope. It is doubtful if the lower threshold due to the $Fe^{58}(\gamma,n)Fe^{57}$ reaction could be observed with this technique, because of the small relative abundance of Fe^{58} and the high yield of photoneutrons from Fe^{57} at that energy. This observed threshold is within the experimental uncertainties of the value, 11.15±0.25 Mev, observed by Sher *et al.*,[2] but is again slightly higher than the value, 11.18±0.04, listed by Way *et al.*[6] Iron presents a relatively favorable situation

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[3] A. H. Wapstra, Physica **21**, 367 (1955).

[4] Kistner, Schwarzchild, Rustad, and Alburger, Phys. Rev. **105**, 1339 (1957).

[5] W. L. Bendel, Bull. Am. Phys. Soc. Ser. II, **2**, 143 (1957).

[6] *Nuclear Level Schemes, A = 40 − A = 92,* compiled by Way, King, McGinnis, and van Lieshout, U. S. Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

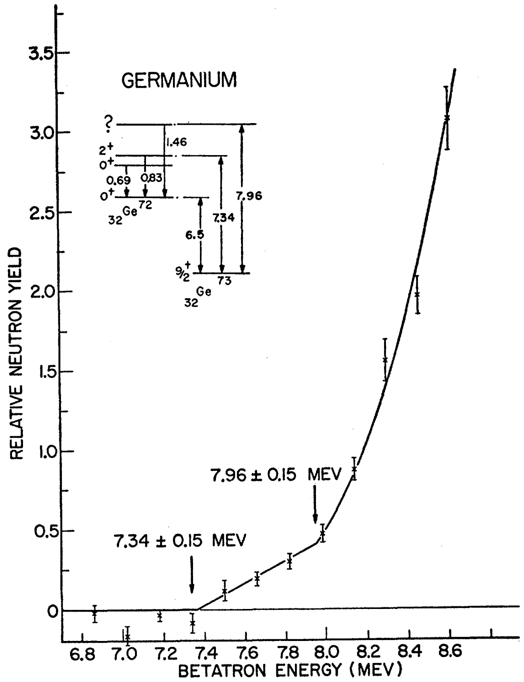

FIG. 4. Photoneutron yield from germanium as a function of betatron energy.

for observation of the thresholds of these two isotopes. The more abundant higher-threshold isotope apparently provides enough photoneutrons to be detectable in the presence of the yield from the less abundant lower-threshold isotope. In addition, the differences in the spins of the initial and final nuclei are small enough to permit the reactions to proceed with dipole absorption of radiation and *s*-wave emission of neutrons.

B. Germanium

The sample consisted of 163 grams of high-purity germanium metal slugs contained in a glass bottle. A similar empty glass bottle was irradiated at the same energies to provide background data. The net neutron yield as a function of betatron energy, plotted in Fig. 4, shows two breaks: one at 7.34±0.15 Mev and one at 7.96±0.15 Mev. A comparison of these values with the binding energies listed in Table I shows a considerable disagreement which could be resolved only if the reaction resulted in excited levels of Ge^{72} instead of the ground state. Since Ge^{73} has a spin of 9/2 and Ge^{72} has a spin of 0, one might expect the reaction, $Ge^{73}(\gamma,n)Ge^{72}$ (ground state), to be strongly inhibited near threshold, and an apparent threshold to appear when the 0.83-Mev excited level[7] (spin = 2) is formed. Assuming this to be the case, the binding energy can be calculated from the observed threshold (7.34 Mev) minus the excitation of the residual nucleus (0.83 Mev) to be 6.51±0.16 Mev, which is in agreement with the value of 6.4±0.1 Mev listed by Way *et al.*[6]

Similarly the break at 7.96 Mev can be associated with the formation of the 1.46-Mev level[6] and the binding energy calculated to be 6.50±0.16 Mev, again in agreement with the above data. One may further postulate that the spin of the 1.46-Mev level in Ge^{72} is very likely 2 or larger, in order to explain the fact that the break at 7.96 Mev appears comparable to that at 7.34 Mev.

C. Rubidium

The sample consisted of 32 grams of rubidium metal in a glass vial. A similar empty glass vial was irradiated to determine background. By the use of the neutron detection equipment only one break was observed in the region between 9.3 and 12.0 Mev and is shown in Fig. 5.[8] This break occurs at 9.89±0.05 Mev, which agrees well with the value of 9.91±0.01 Mev listed by Way *et al.*[6] as the Q value for $Rb^{87}(\gamma,n)Rb^{86}$. The threshold of the $Rb^{85}(\gamma,n)Rb^{84}$ reaction, expected around 10.26 Mev, does not appear in the neutron yield, apparently being obscured by the high neutron yield from Rb^{87} at that energy.

In order to ascertain that the 9.89-Mev break was associated with the $Rb^{87}(\gamma,n)Rb^{86}$ reaction, eight-hour irradiations were made of rubidium samples at betatron energies of 9.3 Mev and 10.3 Mev. The induced radioactivity was detected by flat disk-shaped mica-window Geiger counters. The effect of the 0.27-Mev natural beta radiation from Rb^{87} was reduced by 25-mg/cm² aluminum absorbers. No residual activity was observed in the sample irradiated at 9.3 Mev, but an activity with a 20-day half-life was observed in the sample irradiated

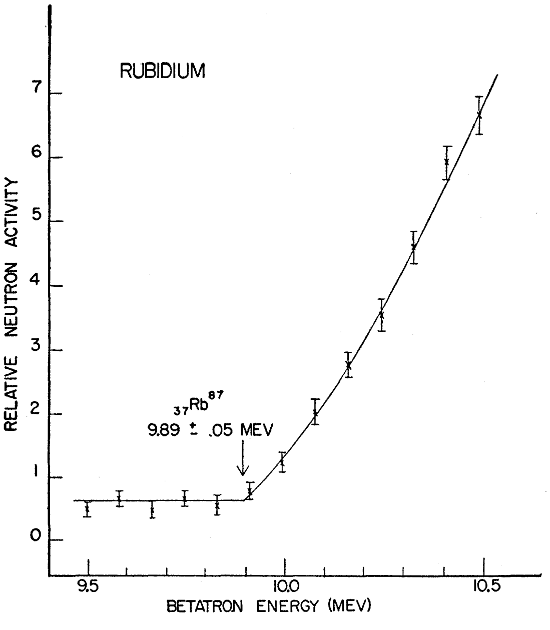

FIG. 5. Photoneutron yield from rubidium as a function of betatron energy.

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[7] G. M. Temmer and N. P. Heydenburg, Phys. Rev. 104, 967 (1956).

[8] The thresholds for rubidium quoted in reference 1 were later found to be in error and were attributed to an impurity in the glass container.

at 10.3 Mev. This 20-day activity can be associated with the 18.6-day Rb^{86} identified by Niday.[9]

In order to measure the $Rb^{85}(\gamma,n)Rb^{84}$ threshold, observations were made of the induced 21-minute activity of the isomeric state of Rb^{84}. A NaI(Tl) crystal ($1\frac{3}{4}$ in. diameter by 2 in. long) was used with a photomultiplier and a 20-channel pulse-height analyzer to detect the 217- and 249-kev cascade gamma rays[10] from the isomeric state. The relative activity as a function of betatron energy is shown in Fig. 6. The threshold appears at 10.98±0.07 Mev. Subtracting the 0.466-Mev[10] excitation energy of the residual nucleus, one obtains 10.51±0.08 Mev for the neutron binding energy. This value also appears higher than the value 10.26 ±0.07 Mev listed by Way *et al.*[6] and perhaps should be considered only as an upper limit. The rather large spin change required (from $\frac{5}{2}$ in Rb^{85} to 6 in the 0.466-Mev state of Rb^{84}) might well inhibit this (γ,n) reaction close to threshold.

D. Hafnium

The sample[11] consisted of a bar of hafnium crystals weighing 1220 grams. Only a portion of this sample was effective in producing detectable neutrons because of its size. The relative neutron yield is shown as a function of betatron energy in Fig. 7. Two breaks appear: one at 6.52±0.12 Mev and one at 6.70±0.09 Mev.

Mass data in the region of hafnium are not known well enough to permit accurate calculations of neutron binding energies; therefore, the assignment of the hafnium thresholds observed in this experiment must be considered tentative. The assignments made here are based on mass values as calculated by Metropolis and Reitwiesner[12] from the empirical mass formula. With this qulification the breaks observed at 6.52 Mev and 6.70 Mev are associated with the $Hf^{179}(\gamma,n)Hf^{178}$ and $Hf^{177}(\gamma,n)Hf^{176}$ reactions, respectively. However, since the differences in spins of the initial and final nuclei are so large for these two reactions ($\Delta I=9/2$ and $\Delta I=\frac{7}{2}$, respectively), it is quite possible that the breaks observed involve excited states of either or both of the residual nuclei.

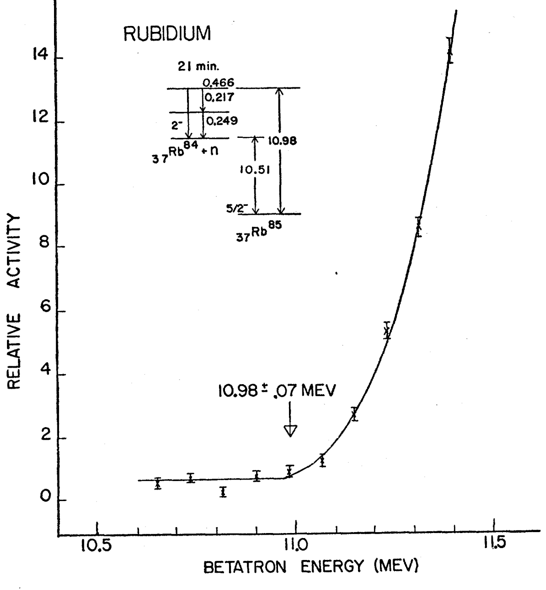

FIG. 6. Relative activity of the 21-minute isomeric state of Rb^{84} as a function of betatron energy.

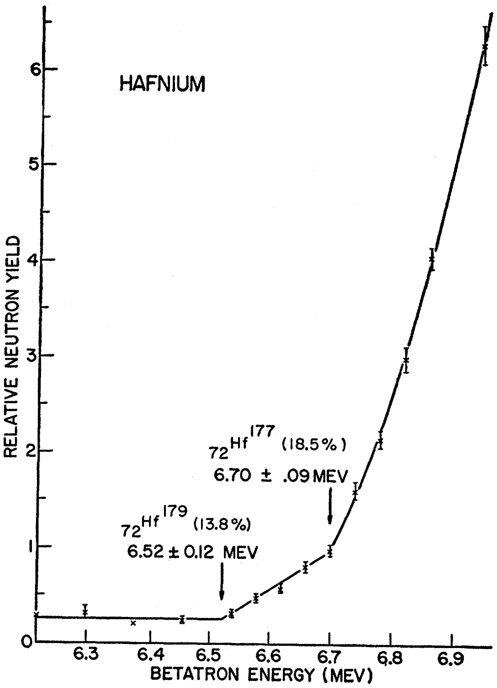

FIG. 7. Photoneutron yield from hafnium as a function of betatron energy.

IV. CONCLUSIONS

The neutron-detection method of determining (γ,n) thresholds has been shown to be very useful for many isotopes where the radioactivity methods are not feasible. However, one should be extremely cautious in deriving neutron binding energies from observed thresholds. Often the ground state is not produced as readily as an excited state, as was shown in the case of germanium. The observed threshold will always represent an upper limit for the binding energy, as long as one is assured that the calibration of the betatron energy has not been adversely affected by similar effects in the calibration thresholds.

V. ACKNOWLEDGMENT

The authors wish to thank W. L. Bendel for his considerable aid in performing many of the measurements and interpretations for the energy calibration of the betatron.

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[9] J. B. Niday, Phys. Rev. 98, 42 (1955).

[10] W. O. Doggett, Ph.D. dissertation, June, 1956, University of California (unpublished).

[11] We are greatly indebted to the Knolls Atomic Power Laboratory for the generous loan of this sample.

[12] N. Metropolis and C. Reitwiesner, Atomic Energy Commission Report NP-1980 (unpublished).