Photonuclear Studies with Monoenergetic Gamma Rays from Thermal Neutron Capture*†

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Monoenergetic γ rays produced when neutrons are captured in various materials have been used to study the following reactions: $Ta^{181}(\gamma,n)Ta^{180m}$(8.15 hr), $Au^{197}(\gamma,n)Au^{196}$(5.6 days), $Ho^{165}(\gamma,n)Ho^{164}$(34 min), $Ag^{107}(\gamma,n)Ag^{106}$(24 min), and $Nb^{93}(\gamma,n)Nb^{92}$(10 days). Cross sections for these reactions have been obtained at several discrete energies between 7.5 and 10.8 Mev. Estimates were also made of the thresholds of these reactions. Two of the thresholds so obtained, $Ta^{181}(\gamma,n)Ta^{180m}$, $E_t=7.60\pm0.08$, and $Nb^{93}(\gamma,n)Nb^{92}$, $E_t=8.99\pm0.04$, have precisions comparable with those of previous measurements of the same quantities.

INTRODUCTION

In recent years there has been much study of the interaction of photons with nuclei. In most of this previous work, the bremsstrahlung produced by electron accelerators has been used as the source of photons. Because of the nature of the bremsstrahlung spectrum, values for reaction cross sections are obtained from the measurements only with some difficulty. Further, although the energy stability of betatrons is good, the absolute determination of the maximum energy of a betatron bremsstrahlung spectrum is difficult.[1]

In the work described below, we have used monoenergetic γ rays in an attempt to check some cross sections and thresholds of photoneutron reactions obtained using bremsstrahlung. The monoenergetic γ rays employed were those produced by the radiative capture of thermal neutrons in various materials. Briefly the experimental procedure is as follows: a small foil of the material whose (γ,n) cross section is to be measured is taped to a piece of the material to be used as a γ-ray source. The assembly is placed near the end of a thermal column adjacent to the Penn State reactor, and the activity induced in the foil by (γ,n) reactions is determined. From this activity the cross section for the (γ,n) reaction is deduced. By using different (γ,n) sources, which produce various γ-ray energies, some notion of the energy dependence of the (γ,n) cross sections can be obtained, over a small range of energies. In a few cases these cross-section curves can be extrapolated with some confidence to the zero-cross-section intercept, and the (γ,n) threshold thus can be obtained.

Wherever possible, we have compared our results with those obtained using the bremsstrahlung spectrum. Previous studies of (γ,n) reactions with monoenergetic gamma rays have been done primarily with proton-capture γ rays.[2] The energies of these γ rays do not overlap the energies employed in this study. One previous use of neutron-capture gamma rays has been reported.[3]

NEUTRON-CAPTURE GAMMA RAYS

Many elements emit only a few monoenergetic neutron-capture γ rays in the energy range from 5 to 11 Mev. The spectra and intensities of these γ rays have been measured at other laboratories and two compilations of recent revised data have been published.[4,5] The energies of neutron-capture γ rays are generally very well known, as evidenced by the good agreement (usually to within 0.1%) of independent determinations. Intensity determinations, i.e., γ-rays emitted per radiative neutron capture, seem subject to greater uncertainties. The quoted accuracy of intensity determinations ranges from 20% for strong, well-defined peaks to as much as 100% for weak or partially resolved peaks.[4,5]

The γ rays employed in this study are listed in Table I. Where intensity measurements differ, we have used the average of the measurements reported in references 4 and 5. The uncertainties in the γ-ray intensities shown in Table I were inferred by us from the discussions of Bartholomew and Higgs,[4] and of Groshev *et al.*,[5] using the arbitrary criterion that intensities greater than 0.1 γ ray per radiative neutron capture indicate strong peaks. In no case did we assign an uncertainty to a γ-ray intensity which was smaller than the errors imposed both by Bartholomew and Higgs and by Groshev *et al.* Uncertainties in the γ-ray intensities constitute one of the largest sources of experimental error in this study.

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[1] A. S. Penfold and E. L. Garwin, Phys. Rev. **115**, 420 (1959).

[2] W. H. Hartley, W. E. Stephens, and E. J. Winhold, Phys. Rev. **104**, 178 (1956).

[3] V. O. Eriksen and C. P. Zaleski, J. phys. radium **15**, 492 (1954).

[4] G. A. Bartholomew and L. A. Higgs, Atomic Energy of Canada Limited 669, 1958 (unpublished).

[5] L. V. Groshev, V. W. Lutsenko, A. M. Demidov, and V. I. Pelekhov, *Atlas of Gamma Ray from Radiative Capture of Thermal Neutrons* (Pergamon Press, New York, 1959); see also L. V. Groshev, B. P. Adyasevich, and A. M. Demidov, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (Columbia University Press, New York, 1956), Vol. 2, p. 39.

TABLE I. Intensities of neutron-capture gamma rays.

Gamma emitter	Energy (Mev)	Intensity (γ-ray per radiative neutron capture) Bartholomew and Higgs[a]	Groshev *et al.*[b]	Average[c]
Cobalt	7.49	0.03	0.027	0.029 ±30(%)
Aluminum	7.73	0.20	0.24	0.22 ±20
Copper	7.91	0.17	0.22	0.20 ±25
	7.63	0.08	0.11	0.10 ±30
Chlorine	8.56	0.014	0.028	0.021 ±50
	7.78	0.07	0.078	0.074 ±25
Nickel	8.997	0.26	0.28	0.27 ±20
	8.52	0.11	0.123	0.12 ±25
	8.11	0.025	0.025	0.025 ±25
	7.82	0.06	0.06	0.06 ±25
Iron	10.16	0.0006	···	0.0006±75
	9.30	0.02	0.027	0.024 ±40
	8.87	0.003	0.003	0.003 ±50
	8.34	0.006	0.002	0.004 ±75
	7.64	0.29	0.315	0.30 ±20
Chromium	9.72	0.05	0.07	0.06 ±30
	8.88	0.14	0.20	0.17 ±30
	8.49	0.05	0.09	0.07 ±40
	7.93	0.06	0.11	0.09 ±40
Nitrogen	10.83	0.11	0.15	0.13 ±30
	9.15	0.01	0.02	0.02 ±50
	8.31	0.04	0.02	0.03 ±50

[a] See reference 4.
[b] See reference 5.
[c] Uncertainties, in percent, estimated as discussed in text.

All of the γ-ray sources listed in Table I emit, in addition to those listed, one or more γ rays in the energy range from 0 to 7.5 Mev. Since these γ rays are below the thresholds for the reactions studied here, they have no effect on the measurements. Aluminum, for example, emits only a 7.73 Mev γ ray in the energy range above 7.5 Mev. Thus, aluminum is effectively a monoenergetic γ-ray source when employed in the study of a reaction whose threshold is at 7.5 Mev or above.

It can be noted from Table I that several of the γ-ray sources employed emit two or more γ rays above the energy threshold of the reactions studied. In such cases, the contribution due to all but one γ ray must be previously determined in order to measure the effect due to that one γ ray. When the chlorine source, for example, is used in the study of the photoneutron reaction in tantalum, the cross section at 7.78 Mev is previously determined from measurements with the aluminum source. The cross section for the 8.56-Mev chlorine γ ray can then be deduced.

PROCEDURE

The various γ-ray sources were placed in the neutron flux near the end of the thermal column of the PSU reactor. The experimental arrangement (see Fig. 1) was located in a bismuth cup and consisted of: (a) a small gold foil approximately $\frac{1}{8}$-inch square by 0.005-inch thick, (b) one of several γ-ray sources in the form of a disk $2\frac{1}{2}$ inches in diameter by $\frac{1}{2}$ inch thick, (c) a second similar gold foil, (d) a boron-loaded plastic disk $2\frac{3}{4}$ inches in diameter by $\frac{5}{8}$ inch high with a depression in its top face $1\frac{1}{2}$ inches in diameter by $\frac{5}{16}$ inch deep, (e) the sample under investigation in the form of a small metal foil, and (f) a lid of borated plastic to enclose the sample completely.

This combination was held together by waterproof cellophane tape and lowered into a bismuth cup on the graphite thermal column adjacent to the Penn State reactor.

The thermal-neutron flux within the bismuth cup was approximately 10^9 neutrons cm^{-2} sec^{-1} which resulted in γ-ray fluxes of the order of 10^7 γ cm^{-2} sec^{-1} at the sample. The samples were irradiated for periods of 30 minutes to several hours. The radioactivity of the photon-induced isotopes was detected by scintillation methods.

The bismuth cup served as a holder for the experimental arrangement and also served to attenuate γ rays from the structural aluminum around the thermal column in order to minimize spurious (γ,n) reactions in the sample. Bismuth itself emits no neutron-capture γ rays above 5 Mev and thus contributed no spurious background. Further, the capture cross section of bismuth for thermal neutrons is low, so that it does not attenuate the neutron flux much.

A background measurement was performed for each reaction studied to determine the amounts of activity from spurious gamma radiation as well as from $(n,2n)$ reactions caused by fast neutrons. These background measurements were performed by irradiating samples with γ-ray sources whose highest energy γ ray was below threshold for the reaction being studied. A measurable background was present only in the tantalum and niobium reactions.

The borated plastic box served to reduce neutron capture in the sample under investigation. Neutron

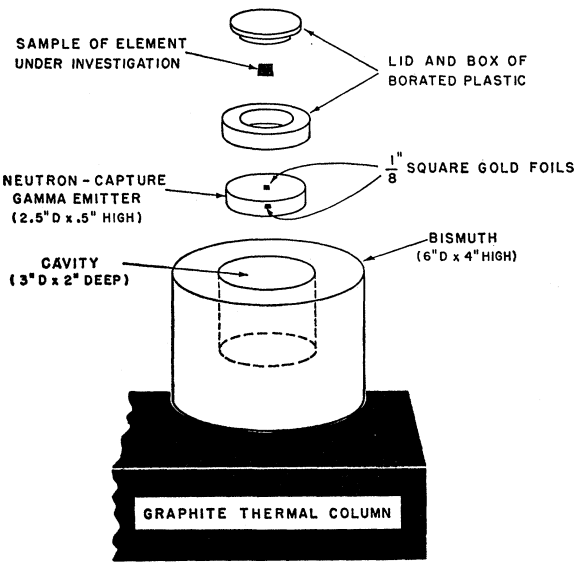

FIG. 1. Experimental arrangement, exploded view.

TABLE II. Summary of measured cross sections.

γ-ray source / Energy (Mev) / Reaction	Co 7.49	Fe 7.64	Al 7.73	Cu 7.91	Cl 8.56	Ni 8.997	Fe 9.30	Cr 9.72	Fe 10.16	N 10.83
$Ta^{181}(\gamma,n)Ta^{180m}$	0±0.05	0.5±1	4.8±1.6	14±5	32±16	44±15	···	83±33	···	120±48
$Au^{197}(\gamma,n)Au^{196}$	···	···	···	0±2	34±17	44±11	64±30	80±30	···	···
$Ho^{165}(\gamma,n)Ho^{164}$	···	···	···	0±0.1	29±15	30±18	46±21	86±31	···	260±93
$Nb^{93}(\gamma,n)Nb^{92}$	···	···	···	···	···	0.008±0.005	1.0±0.4	2.4±0.7	···	···
$Ag^{107}(\gamma,n)Ag^{106}$	···	···	···	···	···	0±0.1	···	4.4±1.5	22±16	23±7.5

capture in the sample was undesirable, since it induced activities in the foil other than that being studied.

The γ-ray sources consisted of disks of iron, copper, nickel, aluminum, and cobalt metal, and sodium chloride, melamine, and chromium-loaded plastic. Each of the γ-ray sources was checked for impurities which could give rise to γ rays in sufficient numbers to be significant. The sodium chloride disk served as a chlorine emitter in this experiment with no correction required for the sodium γ rays since it has been shown that there are no sodium neutron-capture γ rays with energy above 7.0 Mev.[4,5] All sodium γ rays were thus well below the thresholds for the reactions studied.

The gold foils at the top and bottom of the sources were used to measure the thermal neutron flux, so that the rates of neutron capture in the sources could be determined.

Photon-induced activities of the sample foils were detected with a 2 in. by 2 in. NaI(Tl) crystal and multiplier phototube connected to a single-channel differential discriminator. A printer recorded the cumulative counts at preset time intervals. The theoretical calculations of Miller *et al.*[6] were used to determine crystal efficiency.

The activities so measured were corrected for detector efficiency, foil self-shielding, the decay scheme of the photon-induced isotopes and the contribution of other photon energies, to yield a reaction rate, R_r. This reaction rate is related to the (γ,n) cross section, σ_p, by the expression,

$$R_r=\sigma_p F N, \quad (1)$$

where N is the number of atoms in the foil and F is the γ-ray flux at the foil. To determine the γ-ray flux, F, one must know the rate at which neutrons are captured in the γ-ray source, the number of γ rays emitted per neutron capture, the attenuation of γ rays between the source and the sample, and the solid angle subtended by the sample. The calculation of this quantity, F, is described in the Appendix.

The major uncertainties in the photoneutron cross sections obtained from Eq. (1) result from (a) uncertainties in the decay schemes of the photon-induced isotopes, and (b) uncertainties in the intensities of the neutron-capture γ rays.

[6] W. F. Miller, J. Reynolds, and W. J. Snow, Rev. Sci. Instr. **28**, 717 (1957).

RESULTS AND DISCUSSION

Cross sections measured for each reaction are listed in Table II. Each of the cross sections is the result of at least two, and sometimes three, independent measurements. Thresholds, or limits to thresholds are listed in Table III, together with threshold values obtained by other experimenters. The individual measurements are discussed below.

(A) $Ta^{181}(\gamma,n)Ta^{180m}$(8.15 hr)

This reaction was detected through measurement of the 0.054-Mev K x ray which follows K capture and internal conversion in the decay of Ta^{180m}. From the decay scheme of Brown *et al.*[7] one expects 0.75±0.19 K x rays per Ta^{180m} disintegration. Some Ta^{182} was also formed, by neutron capture in tantalum, but this was minimized by the boron box. The half-life of Ta^{182} is 115 days, and its decay is thus readily distinguished from that of the 8.15-hour Ta^{180m}. Ta^{182m}(16 min) was also present; counting was begun after it had decayed.

The cross section for this reaction was measured at 7.49, 7.64, 7.73, 7.91, 8.56, 9.00, 9.72, and 10.83 Mev. A plot of the cross section vs energy is shown in Fig. 2. Also in Fig. 2 is a smooth curve showing the results of Fuller and Weiss[8] for the reaction $Ta^{181}(\gamma,n)Ta^{180}$. It should be emphasized that since they measured neutron

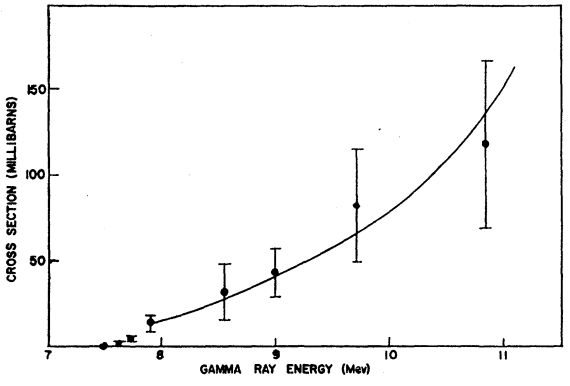

FIG. 2. Cross section vs energy for $Ta^{181}(\gamma,n)Ta^{180m}$(8.15 hr). The smooth curve represents the data of Fuller and Weiss,[8] for the reaction $Ta^{181}(\gamma,n)Ta^{180}$.

[7] H. N. Brown, W. L. Bendel, F. J. Shore, and R. A. Becker, Phys. Rev. **84**, 292 (1951).

[8] E. G. Fuller and M. S. Weiss, Phys. Rev. **112**, 560 (1958).

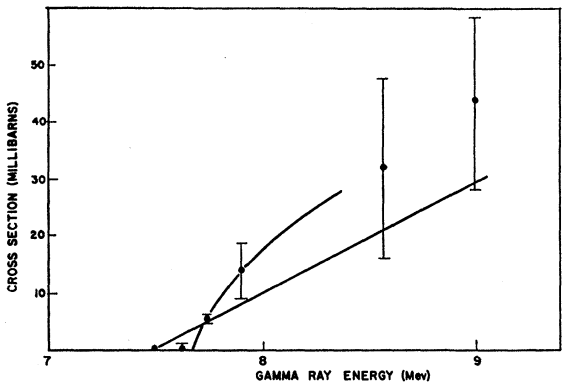

FIG. 3. Cross section for $Ta^{181}(\gamma,n)Ta^{180m}$(8.15 hr) near threshold. The curves indicate possible limits for the threshold of the reaction.

yields rather than induced activities, the data of Fuller and Weiss for this reaction are not necessarily directly comparable to ours.

The cross-section data indicate that the limits of the threshold for the $Ta^{181}(\gamma,n)Ta^{180m}$ reaction are between 7.49 and 7.73 Mev. It should be recalled that the error on our value of the cross section at 7.73 Mev arises primarily from uncertainties in the intensity of the aluminum capture gamma ray and in the decay scheme of Ta^{180m}. Our confidence that activity was observed, that is, that the cross section is not zero at 7.73 Mev, is considerably better than indicated by the quoted uncertainty of the cross section at this energy. The point at 7.64 Mev, obtained using an iron γ-ray source, has such a large error that it is not possible to determine unambiguously whether or not the cross section is greater than zero at this energy. This large error results from the difficulty encountered in correcting for the contribution of the 9.30-Mev γ ray from iron. In only one other instance (see part D below) did the effect of extraneous γ rays introduce an error in the final cross section which was significant compared to other uncertainties.

In order to estimate more closely the threshold for this reaction, the first six points of Fig. 2 are replotted in Fig. 3. The curves in these figures show our estimate of the reasonable limits for the shape which the cross-section curve can have near threshold. From these limits, a value of $E=7.60\pm0.08$ Mev is obtained for the threshold of the reaction. This value is considerably below the value of 7.82 ± 0.026 Mev quoted by Geller, Halpern, and Muirhead[9] for the threshold of the $Ta^{181}(\gamma,n)Ta^{180m}$(8.15 hr) reaction.

B. $Au^{197}(\gamma,n)Au^{196}$(5.6 day)

This reaction was measured by detection of the 0.065-Mev x ray resulting from K-electron capture and internal conversion in the K shell.

Since the number of K x rays emitted per Au^{196} disintegration has not been determined, a subsidiary measurement was required in order to determine the Au^{196} activity. One of the irradiated gold samples was counted simultaneously with the single-channel analyzer and with a multichannel analyzer. The former was adjusted to count 0.065-Mev x rays and the other counted 0.331- and 0.354-Mev γ rays from the sample. This experiment, together with the results of Thieme and Bleuler,[10] which give the number of 0.331- and 0.354-Mev γ rays per Au^{196} disintegration, indicated that we detected 0.86 ± 0.15 count with the single-channel analyzer per Au^{196} decay.

The measured sections are plotted as a function of γ-ray energy in Fig. 4 together with the cross sections measured by Fuller and Weiss.[8]

Because of the uncertainties in the experimental data and the fact that the lowest measured cross section (at 8.56 Mev) appears to be considerably above threshold, no threshold determination was made for this reaction. This experiment indicates a lower limit for the threshold of 7.91 Mev and an upper limit of 8.4 Mev.

C. $Ho^{165}(\gamma,n)Ho^{164}$(34 min)

The amount of Ho^{164} was measured by counting the 0.045-Mev x ray produced after electron capture and internal conversion in the K shell. From the decay scheme given by Brown and Becker,[11] and the K/L orbital capture ratio calculated by Brysk and Rose,[12] one expects (0.49 ± 0.1) K x ray per Ho^{164} disintegration.

After subtracting activity due to 27.3-hour Ho^{166}, the most radioactive Ho^{164} sample was determined (by a least-squares fit over 4 half-lives) to have a half-life of 33.6 ± 1 minutes. Half-lives in the range from 33 to 35 minutes were obtained from the other

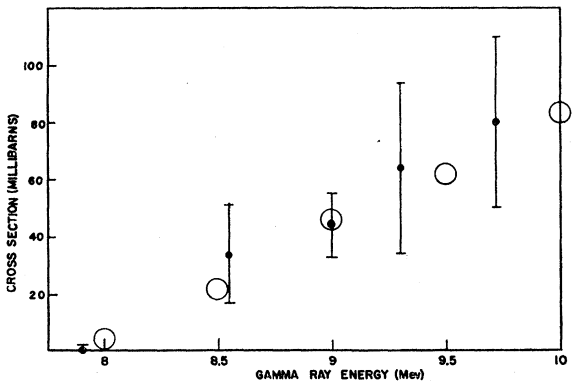

FIG. 4. Cross section vs energy for the $Au^{197}(\gamma,n)Au^{196}$(5.6 day) reaction. The circles are the data of Fuller and Weiss.[8]

[9] K. N. Geller, J. Halpern, and E. G. Muirhead, Phys. Rev. **118**, 1302 (1960).

[10] M. T. Thieme and E. Bleuler, Phys. Rev. **101**, 1031 (1956).

[11] H. N. Brown and R. A. Becker, Phys. Rev. **96**, 1372 (1954).

[12] H. Brysk and M. E. Rose, Oak Ridge National Laboratory Report ORNL-1830, 1955 (unpublished).

samples. Previous measurements of this half-life range from 34±0.5 minutes to 41.5 minutes.[13] Since our result indicated that the lower value is more accurate, a value of 34 minutes was used for the half-life of Ho^{164}.

Data were obtained for this reaction at five energies in the range from 8.56 to 10.8 Mev, plus one point below threshold. Figure 5 shows the cross section for this reaction as function of energy. The threshold is definitely above the 7.91-Mev copper γ ray and below the 8.56-Mev chlorine γ ray. The experiment indicates a lower limit for the threshold of 7.91 Mev and an upper limit of 8.4 Mev.

Previous measurements of the threshold for this reaction are in agreement with the limits assigned by this experiment (see Table III). The relative cross section has been reported in histogram form by Fuller, Petree, and Weiss.[14] The shape of Fig. 5 would agree well with a smooth curve through their histogram.

D. $Ag^{107}(\gamma,n)Ag^{106}$(24 min)

Ag^{106} emits a 0.513-Mev γ ray and also decays by positron emission which contributes 0.511-Mev annihilation radiation.

Both of these radiations were counted by the spectrometer. Using the decay scheme given by Bendel *et al.*,[15] the spectrometer should count 0.76±0.08 pulses of about 0.51 Mev per Ag^{106} disintegration.

The relatively high threshold for this reaction does not make it especially amenable to measurement by these methods. The results are tabulated in Table II. The data obtained with the iron γ-ray source suggest that either the intensity of the weak, 10.16-Mev, iron gamma ray is about 75% above the reported value (within the limits of experimental error for a gamma ray this weak), or the 9.30-Mev iron gamma ray is slightly above the threshold of the reaction being studied. [σ_p(9.30 Mev)<0.5 mb.] The former choice seems more probable in the light of the threshold data obtained by others.[9,16] The results of this experiment suggest limits of 9.30 Mev and 9.6 Mev on the threshold for this reaction.

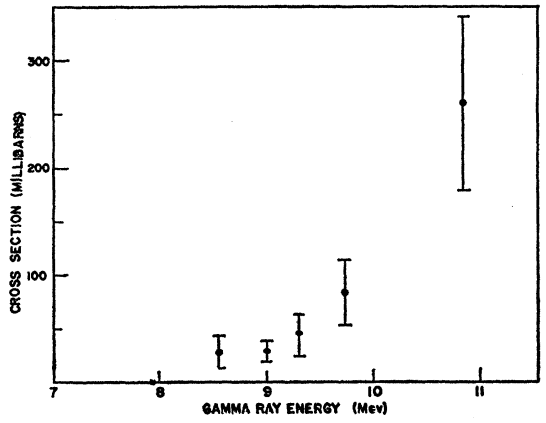

FIG. 5. Cross section vs energy, $Ho^{165}(\gamma,n)Ho^{164}$(34 min).

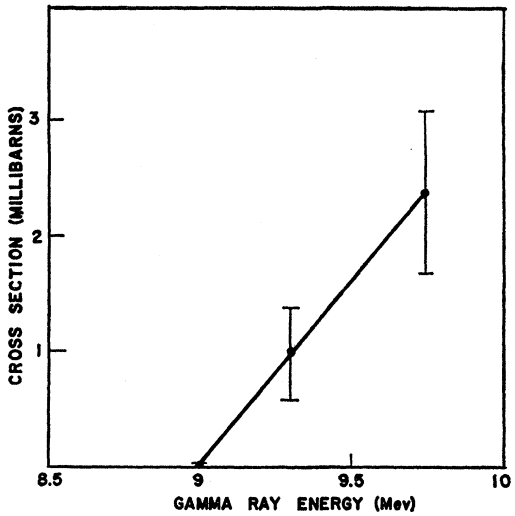

FIG. 6. Cross section vs energy $Nb^{93}(\gamma,n)Nb^{92}$(10 day). The line indicates a possible extrapolation to threshold.

E. $Nb^{93}(\gamma,n)Nb^{92}$(10 days)

Ten-day Nb^{92} was observed by detecting the 0.930-Mev γ ray emitted in its decay. From the decay scheme given by Strominger *et al.*,[12] 0.98 such γ rays are emitted per Nb^{92} disintegration. Nb^{94}, which has a 20 000 year half-life could not be observed. Some Ta^{182}(115-day), formed by neutron capture in a tantalum impurity in the niobium, was detected in the irradiated niobium foils.

Results of the measurements on this reaction are shown in Fig. 6. The measured value of the cross section at 8.997 Mev is extremely small. However, the Nb^{92} activity measured at this energy was about five times the statistical uncertainty of that activity. Therefore, the cross section at 8.997 Mev is probably greater than zero. The $Nb^{93}(\gamma,n)Nb^{92}$(10-day) threshold obtained from the intercept of a straight line through the data of Fig. 6 is 8.99 Mev, with an uncertainty of about 20 kev. In order to allow for other reasonable extrapolations of the data, we estimate that the threshold of this reaction is 8.99±0.04 Mev. This

[13] D. Strominger, J. M. Hollander and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).
[14] E. G. Fuller, B. Petree, and M. S. Weiss, Phys. Rev. **112**, 554 (1958).
[15] W. L. Bendel, F. J. Shore, and R. A. Becker, Phys. Rev. **90**, 888 (1953).
[16] W. J. Bendel, J. McElhinney, and R. A. Tobin, Phys. Rev. **111**, 1297 (1958).

TABLE III. (γ,n) thresholds.

Reaction	Threshold, E_t (Mev)	Reference
$Ta^{182}(\gamma,n)Ta^{180m}$ (8.15 hr)	7.60 ±0.08	This study
	7.852±0.026	9
$Nb^{93}(\gamma,n)Nb^{92}$ (10 day)	8.99 ±0.04	This study
	8.78 ±0.06	9
	8.86 ±0.05	7
$Ag^{107}(\gamma,n)Ag^{106}$	$9.30<E_t<9.6$	This study
	9.353±0.034	9
	9.43 ±0.05	16
$Au^{197}(\gamma,n)Au^{196}$	$7.91<E_t<8.4$	This study
	8.057±0.022	9
	7.96 ±0.07	17
$Ho^{165}(\gamma,n)Ho^{164}$	$7.91<E_t<8.4$	This study
	8.16 ±0.08	9
	8.10 ±0.05	17

value is somewhat higher than those of Geller *et al.*,[9] and Chidley *et al.*[17] given in Table III.

ACKNOWLEDGMENTS

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APPENDIX

The γ-ray flux, F, at the sample position from a source containing ρ nuclei per cm^3, which has a thermal-neutron capture cross section, σ, and which emits y photons per radiative capture is given by

$$F=\rho\sigma\Phi y S. \tag{2}$$

In this expression, Φ is the thermal neutron flux at the face of the source which is nearest the reactor (away from the sample position). This flux is measured using gold foils which have been calibrated with a standard neutron source. S is a quantity which includes terms to account for the attenuation of neutrons in the source, the attenuation of γ rays between the source and the sample foil, and the solid angle subtended at the sample by the source. It is obtained from the expression

$$S=\frac{1}{2}\int_{r=0}^{R}\int_{z=h}^{K}\frac{r\,dr\,dz}{z^2+r^2}\exp\left[-\frac{A(z-h)(r^2+z^2)^{\frac{1}{2}}}{z}-\frac{Bh(r^2+z^2)^{\frac{1}{2}}}{z}-C(K-z)\right], \tag{3}$$

where z is the vertical distance from the sample to a unit volume of the source, r is the horizontal distance from the sample to the same unit volume, h is the thickness of the borated plastic, R is the radius of the γ-ray source, and K is the thickness of the source plus the borated plastic.

A is the linear attenuation coefficient of γ rays in the source, B is the linear attenuation coefficient of γ rays in the borated plastic, and C is the linear attenuation coefficient of neutrons in the γ-ray source.

In deriving this expression, it was assumed that the diameter of the sample was much less than the diameter of the γ-ray source, i.e., that the sample could be considered a point. This assumption was justified by our experimental arrangement. It was also assumed that the neutron flux falloff through the source could be considered exponential. This assumption was verified experimentally, and at the same time, the attenuation factor C evaluated. With some manipulation, S can be written

$$S=\frac{e^{-CK}}{2}\int_{z=h}^{K}dz\,e^{Cz}[E_1(z,Q)-E_1((R^2+z^2)^{\frac{1}{2}},Q)], \tag{4}$$

where $Q=A+(B-A)h/z$, and the E_1's are the generalized exponential integral functions, discussed, for example, by Case, deHoffmann, and Placzek.[18] This expression for S was numerically integrated for each source. The γ-ray flux at the sample from each source was then evaluated.

[17] B. G. Chidley, L. Katz, and S. Kowalski, Can. J. Phys. **36**, 407 (1958).

[18] K. M. Case, F. deHoffmann, and G. Placzek, *Introduction to the Theory of Neutron Diffusion* (U. S. Government Printing Office, Washington, D. C., 1953), Vol. I.