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Gamma Rays Following Neutron Capture in Iron,
Sodium, and Thorium*

O. A. Wasson, J. B. Garg,[†] R. E. Chrien,
and M. R. Bhat
Brookhaven National Laboratory, Upton, New York

The intensities of prominent γ rays from neutron capture in iron, sodium, and thorium have been measured as a function of incident neutron energy at the HFBR fast chopper facility at Brookhaven. The partial capture cross section of 27 γ rays in iron was measured from thermal to 5 keV neutron energies. Additional γ rays were observed in the 1167 eV resonance and at thermal energy. In sodium, the observation of a ground state γ ray in the thermal spectrum ($E_\gamma = 6960 \pm 2.0$ keV) with an intensity of ~ 0.1 photons/100 captures supports the 2+ assignment of the 2.85 keV resonance. The γ -ray spectra from capture at thermal and in the four lowest energy S-wave resonances in Th^{232} exhibit large fluctuations in the partial radiation widths.

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[†] State University of New York at Albany, Albany, New York.

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The nuclear properties of iron, sodium, and thorium are of considerable interest because of their use in the nuclear power field. Of prime interest is the measurement of the capture cross section and the resulting γ -ray spectrum as a function of neutron energy. We report the results of such measurements which have been performed at the HFBR fast chopper facility^[1] at Brookhaven National Laboratory. Using the 22-meter flight path, neutron capture γ -ray spectra have been obtained from thermal to 5 keV neutron energies. The γ rays were detected by lithium-drifted Ge diodes of various volumes, yielding a γ -ray energy resolution of ~ 8 keV for 7.6 MeV γ rays in iron. Experimental events were recorded on magnetic tape and subsequently analyzed at the central computer.

Since for iron the average capture cross section is small, $\sigma(0.0025 \text{ eV}) \sim 2.7$ barns, the measurement of the cross section is difficult with the conventional capture tank technique. On the other hand, the γ -ray spectrum produced in neutron capture is characterized by a relatively small number of relatively strong lines. It is therefore feasible to measure the cross sections of individual γ rays in the epithermal neutron energy region. Figure 1 shows the resulting time-of-flight spectrum for γ -ray events above 3.2 MeV ($E_\gamma > 3.2 \text{ MeV}$). The spectrum is dominated by the resonance at 1167 eV.^[2] The structure in the region from 0.1 to 1.0 keV is due to neutrons scattered from the 1/4 in. iron target and captured in the germanium detector, which was shielded with Lithium-6 and polyethylene. The weak germanium capture γ rays presented little difficulty in the analysis of the data.

Structure in the γ -ray yield near 46 eV is observable in Figure 1. Contrary to the higher energy structure, this bump is definitely attributable to iron since it does not appear in a control experiment using an equivalent thickness lead scatterer. A neutron width of $9 \times 10^{-8} \text{ eV}$ is obtained for this resonance by comparison to the area observed for the 1167 eV resonance. This width is subject to a large uncertainty because of spectrum differences and multiple scattering near the 1167 eV resonance. Nevertheless, it is acceptable as an order of magnitude estimate and is most likely to be a P-wave resonance.

The work of Groshev^[3] demonstrates that $\sim 80\%$ of the primary γ -ray transitions have an energy greater than 3.2 MeV. We have used the figure of 83% to normalize our relative thermal intensities to an absolute basis. The presence of several secondary transitions in this region^[4] does not appreciably alter this figure since it is probable that their presence is balanced by primary transitions too weak to be detected and therefore not included in the normalization.

The intensity variation of 27 of the stronger γ rays has been measured in the epithermal region by use of a flux monitor based on the $B^{10}(n, \alpha, \gamma)$ reaction, detecting the 478 keV γ ray. A correction has been applied for neutron absorption in the boron. We have used the fact that the iron capture cross section is proportional to v^{-1} near thermal to normalize our thermal capture run to the data recorded in the epithermal region.

The results of the experiment are given in Table I which lists the partial cross sections of 27 lines from Fe^{56} . The partial radiation widths of the 1167 eV resonance are listed in Table II. It was assumed that 83% of the primary transitions had energies greater than 3.2 MeV and

that the total radiation width was 0.6 eV.

Most of the γ rays follow the $1/v$ cross section rather closely from thermal to 1 keV neutron energies. The partial cross section of a few representative γ rays are shown in Figures 2 and 3. Figure 2 shows the quantity $\sqrt{E} \sigma$ as a function of neutron energy for three γ rays. The region near the 1167 eV resonance has been excluded. The hatched regions indicate the $1/v$ behavior including the uncertainty in the thermal cross section. The 5922 keV γ ray follows the $1/v$ trend quite accurately while ground state doublet at 7645 and 7631 keV shows small variations. Figure 3 shows a similar plot. The point at 2.6 keV may be affected by events associated with the 1167 eV resonance due to the relatively poor neutron energy resolution and is considered less reliable than the other points. The 6382 γ ray follows the $1/v$ law, while the 4463 keV γ ray shows a slight departure from $1/v$.

Portions of the typical γ -ray spectra are shown in Figures 4-6 for the neutron energy regions of Table I. Differences in the spectrum associated with the 1167 eV resonance are clearly seen. Figure 4 shows the variation in γ -ray intensity of the ground state doublet between thermal and the 1167 eV resonance. Of particular interest is the γ ray at 7511.4 keV which feeds a $5/2+$ level in Fe^{57} at 134 keV excitation energy.^[4] This line is weakly seen in the resonance but is not seen at thermal or in the off-resonance region. The isotropic angular distribution of γ rays from the 1167 eV resonance indicates a spin of $1/2$ and therefore, we believe this to be an E-2 transition. Figure 5 demonstrates the large variation for the 7279 and 6382 keV γ rays between thermal and the resonance. The strongest γ ray in the germanium spectrum at 7259 keV is observed in the 100 eV region. Figure 6 compares the thermal spectrum with the off-resonance regions at 54 eV and 2600 eV to establish the cross-sectional variation of the 3268, 3358, 3416, and 3439 keV γ rays.

The implications of the γ -ray intensities observed in the off-resonance region and in the 1167 eV resonance are now under study.

Sodium. The γ -ray spectra produced by capture of thermal and 100 eV neutrons in sodium were found to be similar. However, a weak 6961 keV ground state transition was observed with an intensity of < 0.1 photons per 100 neutrons captured, which has previously been unreported.^[5] If thermal capture is dominated by the 2.9 keV resonance with spin $2+$, as is likely from the known resonance parameters, then the multipolarity of this ground state transition is E-2. The partial radiation width is ~ 600 μeV , which is $\sim .01$ Weisskopf units.

Thorium. In spite of the importance of thorium, little is known of the nuclear properties of the isotope thorium-233. Even its neutron binding energy and ground state spin and parity have not been measured. No excitation energies have been deduced. Only a few weak high energy γ rays have previously been observed in thermal capture by Groshev^[6] and Greenwood.^[7] The neutron time-of-flight spectrum for a $1/4$ in. thorium sample is shown in Figure 7. The γ -ray energies were limited to the region above 2.8 MeV in order to be above the full energy peak of the ThC'' background γ ray at 2614 keV. The γ -ray spectra produced in the four $1/2+$ S-wave resonances at 21.8, 23.4, 59.5, and 69.1 eV are shown in Figure 8.

The γ -ray energy scale which extends from 3.8 to 5.0 MeV refers to the double-escape peaks, although the full energy peaks of lower energy γ rays are also included. The most striking feature of these spectra are the variations in γ -ray intensities from resonance to resonance. These variations are not due to angular momentum selection rules since the resonance spins are $1/2^+$ for all the spectra. This large variation in partial radiation widths is characteristic of the Porter-Thomas distribution which is expected for a complicated nucleus whose properties vary statistically.

The results of various calculations of the neutron binding energy vary between 4779 and 4983 keV as shown by the bar labelled B_n . Groshev^[6] has reported a 4920 keV transition in thermal capture which was not confirmed in this experiment. Weak γ -ray peaks are observed at 4889 and 4862 keV in the 23.4 and 21.8 eV resonances, respectively. Unfortunately, these peaks are only partially resolved from the full energy peaks of other γ rays, and a definite statement that the neutron binding energy exceeds 4889 keV is not justified at this time.

A total of 30 γ rays with energies greater than 2.9 MeV were observed in the various spectra and are listed in Table III along with the deduced partial radiation widths. The γ -ray energies labelled with the symbol F were determined from the full energy peaks; the unlabelled from the double escape peaks. The partial widths were determined by normalizing the relative intensity of the 3.94 MeV γ ray observed in thermal capture to absolute intensity of 0.5 photons per 100 captures given by Groshev.^[6] The total radiation width of each resonance was taken to be 26 meV. The listed errors contain only the statistical uncertainty in the γ -ray peak areas. The absolute error is probably a factor of 2. The strongest γ ray has a width of 400 μ eV.

The ground state spin and parity of thorium-233 is expected to be $1/2^+$ or $7/2^-$ ^[8] based on the Nilsson Model. The $1/2^+$ states would be populated by primary M-1 transitions from the capturing state while the $7/2^-$ states require E-3 transitions. The observation of weak γ rays near the expected neutron binding energy is evidence for the $1/2^+$ assignment. No strong γ rays are observed within ~ 500 keV of the expected ground state transition. If the observed strong γ rays are electric dipole, then the negative parity $1/2^-$ and $3/2^-$ states are located above 500 keV excitation energy. This is similar to the situation observed in U-239.

Asghar, et al.^[9] have measured the total radiation width of the 23.4 eV resonance to be 29.9 meV, which is 39% larger than the mean width of 21.5 meV. This difference was attributed to the Porter-Thomas fluctuation of a few high energy γ rays. Our measurements indicate that the high energy γ rays contribute only 5% of the required increase in the total radiation width of the 23.4 eV resonance, thus supporting the value of 22 meV for the total radiation width of this resonance as measured by Bhat and Chrien.^[10]

In summary, we have measured the partial capture cross section of 27 γ rays in iron and found most of them to follow a $1/v$ dependence. In thorium the γ -ray spectra for the 4 lowest energy S-wave resonances demonstrated large fluctuations in the partial radiation widths.

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Table I

Iron Partial Capture Cross Sections (mb)

E_{γ} , keV	Neutron Energy Range (eV)						
	Thermal	5.67	53.6	136	243	540	2700
7645.4	571 ± 19	38.5 ± 1	11.7 ± 0.3	6.8 ± 0.4	4.3 ± 0.3	3.0 ± 0.2	1.2 ± 0.14
7631.0	666 ± 21	44.8 ± 1	13.9 ± 0.3	8.2 ± 0.4	6.5 ± 0.3	3.6 ± 0.2	1.9 ± 0.18
7511.4	< 1	< 0.1	< 0.05	< 0.10	< 0.10	< 0.10	0.22 ± 0.10
7279.2	128 ± 6	8.0 ± 0.5	2.5 ± 0.15	1.6 ± 0.3	1.0 ± 0.2	0.7 ± 0.1	0.18 ± 0.06
6507.0	3 ± 1	$0.67 \pm .18$	< 0.1	< 0.10	< 0.10	< 0.10	< 0.10
6382.2	14 ± 2	1.0 ± 0.2	0.3 ± 0.06	0.16 ± 0.12	0.15 ± 0.10	< 0.10	0.41 ± 0.11
6020.0	193 ± 4	$12.7 \pm .35$	4 ± 0.1	2.4 ± 0.2	1.6 ± 0.2	1.1 ± 0.2	0.32 ± 0.09
5922.0	184 ± 4	$12.5 \pm .35$	3.9 ± 0.1	2.2 ± 0.2	1.5 ± 0.2	1.2 ± 0.2	0.58 ± 0.12
4950.8	16 ± 2	1.3 ± 0.2	$0.33 \pm .05$	0.30 ± 0.12	0.22 ± 0.11	0.2 ± 0.1	0.12 ± 0.05
4811.7	30 ± 3	$2.0 \pm .3$	$0.69 \pm .08$	0.38 ± 0.14	0.41 ± 0.15	0.08 ± 0.07	0.07 ± 0.06
* 4676.4	7.2 ± 1.5	0.4 ± 0.15	$0.16 \pm .05$	0.27 ± 0.12	< 0.10	0.22 ± 0.11	< 0.10
4463.0	13 ± 2	1.0 ± 0.2	$0.28 \pm .04$	0.31 ± 0.13	< 0.10	0.16 ± 0.09	0.09 ± 0.06
4408.0	32 ± 2	1.8 ± 0.2	$0.58 \pm .05$	0.65 ± 0.16	0.26 ± 0.10	0.27 ± 0.09	< 0.10
4276.8	7 ± 2	$0.35 \pm .15$	$0.24 \pm .04$	$< .10$	< 0.10	0.25 ± 0.10	< 0.10
4220.0	76 ± 4	5.0 ± 0.3	$1.5 \pm .08$	1.05 ± 0.21	0.59 ± 0.16	0.48 ± 0.10	0.06 ± 0.06
* 4014.2	8 ± 2	0.48 ± 0.17	$0.14 \pm .05$	0.15 ± 0.14	< 0.2	< 0.15	< 0.10
3856.6	26 ± 4	2.3 ± 0.3	$0.60 \pm .08$	0.23 ± 0.13	0.32 ± 0.14	< 0.15	< 0.10
* 3794.6	5 ± 2	$.58 \pm .2$	$0.14 \pm .05$	$< .15$	0.2 ± 0.2	< 0.15	0.09 ± 0.07
* 3780.0	6.4 ± 1.5	$.81 \pm .2$	$0.18 \pm .05$	0.13 ± 0.14	< 0.2	< 0.15	< 0.10
3745.3	7 ± 2	$0.49 \pm .19$	$0.17 \pm .05$	$< .15$	< 0.2	< 0.15	< 0.10
3721.3	3.4 ± 1.4	2.0 ± 0.2	$0.08 \pm .05$	0.18 ± 0.15	0.25 ± 0.20	< 0.15	< 0.10
3508.4	4.7 ± 1.6	< 0.2	< 0.05	$< .15$	< 0.2	< 0.15	< 0.10
* 3490.0	11 ± 2	0.5 ± 0.2	0.22 ± 0.06	$< .15$	< 0.2	0.20 ± 0.13	< 0.10
3439.0	35 ± 3	2.1 ± 0.25	0.75 ± 0.10	$< .15$	< 0.2	< 0.15	< 0.10
* 3415.7	35 ± 3	1.7 ± 0.2	0.54 ± 0.09	0.53 ± 0.15	< 0.2	0.21 ± 0.14	< 0.10
* 3358.0	7.6 ± 1.7	0.58 ± 0.18	< 0.05	$< .15$	< 0.2	0.14 ± 0.14	0.22 ± 0.09
3267.7	23 ± 14	1.35 ± 0.3	0.51 ± 0.14	$< .15$	0.4 ± 0.2	0.16 ± 0.12	0.16 ± 0.10

* Non-primary γ ray.

Table II

Partial Radiation Widths of 1167 eV Resonance

E_{γ}, keV	Width (meV) $\Gamma_{\gamma 1}$
7645.4	106 ± 7
7631.0	208 ± 9
7511.4	14.5 ± 3.0
7279.2	4.6 ± 1.7
6507.0	5.5 ± 1.0
6382.2	7.6 ± 2.4
6020.0	7.5 ± 1.6
5922.0	16.2 ± 2.3
4950.8	12.3 ± 2.1
4811.7	< 1.0
* 4676.4	(3.2 ± 1.2)
4463	12.1 ± 2.3
4408	3.6 ± 1.4
4276.8	2.8 ± 1.4
4220.0	2.8 ± 1.4
* 4014.2	(< 1.0)
3856.6	2.6 ± 1.9
* 3794.6	(< 1.0)
* 3780.0	(4.7 ± 2.0)
3745.3	< 1.0
3721.3	3.9 ± 2.1
3508.4	< 1.0
* 3490.0	(< 1.0)
3439.0	< 1.0
* 3415.7	(2.2 ± 1.6)
* 3358.0	(2.9 ± 1.6)
3267.0	3.9 ± 2.5

* Non-primary γ ray.

Table III

Thorium γ -ray Energies and Partial Radiation Widths for
the Indicated Neutron Energies

E_{γ}, keV^c	$\Gamma_{\gamma j}, \mu\text{eV}$				
	$< 1 \text{ eV}^b$	21.8 eV	23.4 eV	59.5 eV	69.1 eV
2965.0 F	< 8	49 ± 20	47 ± 20	< 20	< 20
2979.2 F	< 8	122 ± 22	< 8	< 25	< 20
a 3113.4 F or 4135.4	< 8	55 ± 21	42 ± 20	130 ± 22	< 25
3145.0 F	55 ± 10	< 18	< 18	< 25	< 22
a 3261.7 F or 4283.7	15 ± 8	39 ± 26	88 ± 20	< 28	52 ± 26
3305.6 F	< 13	39 ± 26	78 ± 22	< 40	< 20
a 3319.8 F or 4341.8	< 13	50 ± 26	< 20	< 28	52 ± 26
3336.6 F	17 ± 10	29 ± 26	166 ± 25	< 28	< 18
a 3349.5 F or 4371.5	< 10	50 ± 25	55 ± 20	177 ± 30	< 20
a 3393.3 F or 4415.3	20 ± 10	< 20	44 ± 20	88 ± 30	< 18
3430.0 F	75 ± 10	< 20	42 ± 20	< 28	< 18
3459.1 F	< 10	< 25	< 20	148 ± 30	52 ± 20
3473.3 F	135 ± 20	< 20	< 20	< 16	70 ± 20
a 3501.3 F or 4523.3	36 ± 10	< 20	42 ± 20	< 16	< 18
3525.0 F	67 ± 12	60 ± 26	20 ± 20	< 31	< 18
3733.9 F	< 8	< 20	< 18	88 ± 30	< 20
3833.0	88 ± 13	< 39	< 20	117 ± 50	208 ± 40
3856.7	82 ± 13	122 ± 30	166 ± 25	116 ± 50	205 ± 45
3877.4	77 ± 13	< 20	122 ± 25	< 30	< 25
3891.6	< 10	31 ± 20	122 ± 25	< 28	< 25
3951.0	130 ± 15	143 ± 26	< 20	< 28	< 25
3967.7	< 8	39 ± 20	88 ± 26	< 28	< 20
4033.5	< 8	42 ± 26	120 ± 25	< 28	52 ± 20
4043.8	60 ± 15	123 ± 26	167 ± 25	88 ± 45	52 ± 20
4069.6	55 ± 12	20 ± 20	80 ± 26	< 30	78 ± 26
4103.1	20 ± 10	151 ± 20	400 ± 40	< 28	34 ± 26
4198.6	78 ± 10	50 ± 26	55 ± 28	90 ± 30	< 26
4212.8	81 ± 15	180 ± 30	275 ± 30	57 ± 30	310 ± 30
4243.8	78 ± 20	112 ± 26	55 ± 26	90 ± 30	104 ± 26
4861.7	< 8	60 ± 29	< 10	< 15	< 20
4888.8	< 8	30 ± 26	31 ± 20	29 ± 20	< 20

^a Either a full energy peak or a double escape peak.

^b "Effective" width

^c $\pm 2.0 \text{ keV}$

Figure Captions

Figure 1. Iron time-of-flight spectrum.

Figure 2. Iron partial capture cross sections.

Figure 3. Iron partial capture cross sections.

Figure 4. Iron γ -ray spectra.

Figure 5. Iron γ -ray spectra.

Figure 6. Iron γ -ray spectra.

Figure 7. Thorium time-of-flight spectrum.

Figure 8. Thorium γ -ray spectra.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8