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Resonance neutron capture in ^{58}Fe, ^{56}Fe, and ^{54}Fe

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Neutron capture γ-ray measurements following resonance capture have been performed upon enriched samples of ^{54}Fe and ^{58}Fe, and upon a natural Fe (91.7% ^{56}Fe) sample. Twenty-eight γ rays were observed from two resonances of the ^{58}Fe(n, γ) reaction, and nineteen were incorporated into a level scheme for ^{59}Fe. Thirty-seven γ rays were observed from the 1.167-keV resonance of the ^{56}Fe(n, γ) reaction, and twenty-eight were incorporated into a level scheme for ^{57}Fe. Two γ rays were observed from four resonances of the ^{54}Fe(n, γ) reaction. The neutron separation energy for ^{59}Fe was determined to be 6580.8 ± 1.0 keV.

[NUCLEAR REACTIONS ^{54,56}Fe(n,γ), E=1–50 keV, ^{58}Fe (n,γ), E=0.1–11 keV; measured E_γ, I_γ. ^{55}Fe deduced resonances. ^{57,59}Fe deduced resonances, levels. ^{59}Fe deduced neutron separation energy. Enriched targets.]

I. INTRODUCTION

We have carried out a series of (n,γ) measurements following resonance neutron capture on all stable iron isotopes. The present paper describes such measurements carried out on enriched ^{58}Fe and ^{54}Fe targets and on a natural Fe (91.7% ^{56}Fe) sample. The ^{57}Fe(n,γ) measurements will be reported in a future publication.

Previous experimental investigations of the level structure of ^{59}Fe have been carried out primarily by the ^{57}Fe(t,p) and ^{58}Fe(d,p) stripping reactions[1-3] and by the ^{58}Fe(n,γ) reaction with thermal neutrons.[4] We have observed 28 γ rays (8 primary, 20 secondary) from the present ^{58}Fe(n,γ) reaction study. Nineteen of these have been incorporated into a level scheme which includes many of the previously reported levels.[1-5]

We have also observed 37 γ rays (14 primary, 23 secondary) in the ^{56}Fe(n,γ) reaction at the 1.167-keV neutron resonance. A similar measurement has been reported by Chrien *et al.*[6] Twenty-eight of

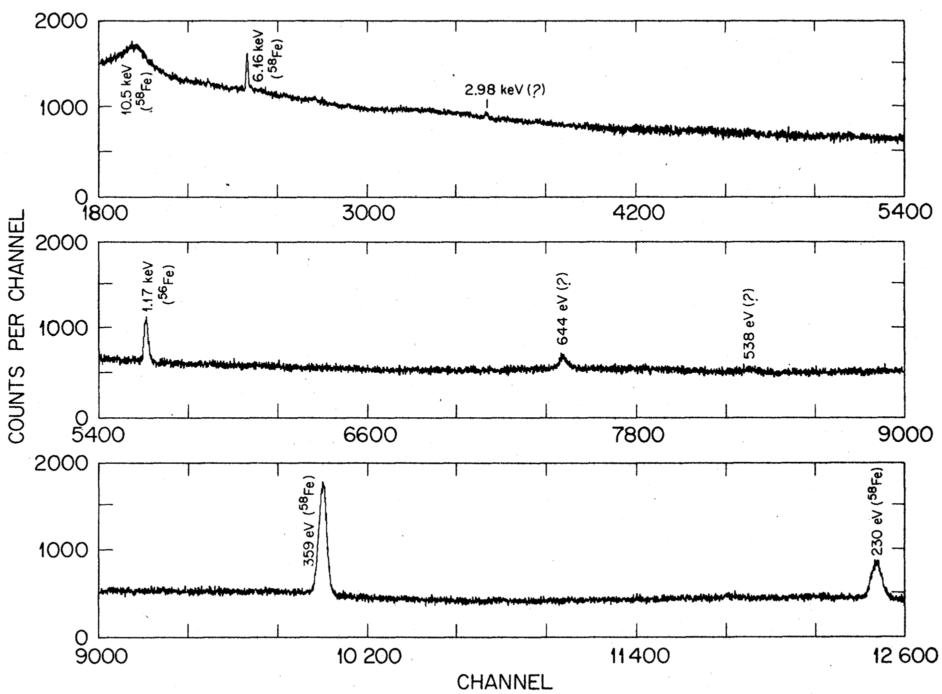

FIG. 1. Counting rate for all γ-ray events above 100 keV *versus* neutron time-of-flight for the enriched ^{58}Fe target. Resonances in ^{56}Fe and ^{58}Fe are identified.

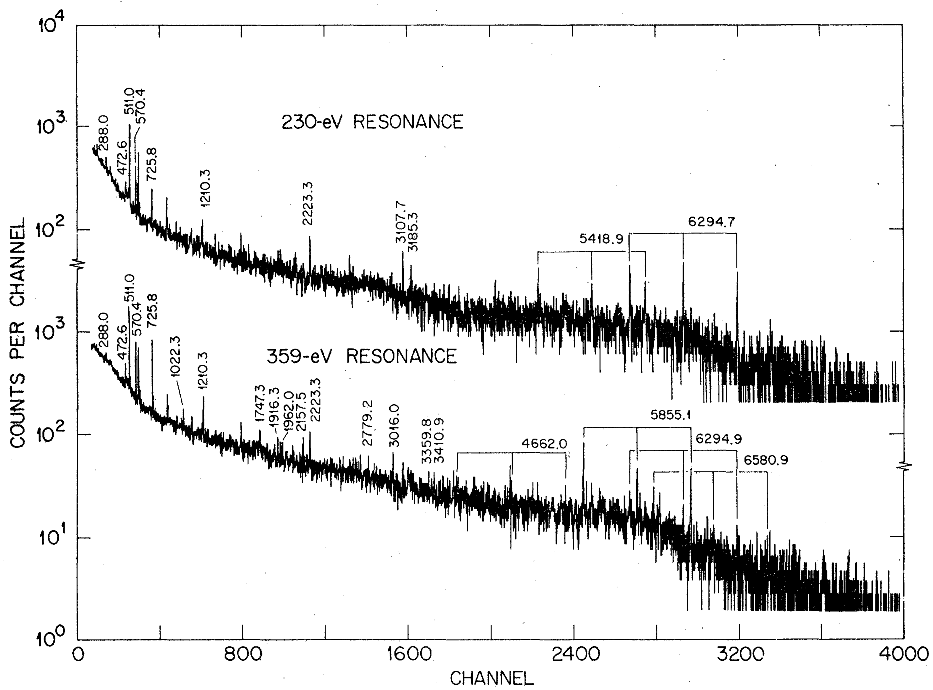

FIG. 2. The γ-ray spectra (without off-resonance background corrections) for the 230-eV and 359-eV neutron resonances in ^{58}Fe. All γ-ray energies are in keV. Only selected peaks are labelled.

TABLE I. Relative photon intensities of the primary γ rays from the $^{58}Fe(n,\gamma)^{59}Fe$ reactions

Other work[a] Thermal (n,γ) measurements		Present work Resonance (n,γ) measurements	230 eV resonance	359 eV resonance
E_γ (keV)	I_γ (%)	E_γ (keV)[b]	I_γ[c]	I_γ[c]
6582	2.3	6580.5 *30*	<0.4	0.99 *30*
6295	51.0	6294.5 *20*	3.7 *4*	0.96 *32*
		No 6108.2[d]	<0.4	<0.3
		6010.4 *30*	<0.4	0.78 *28*
5854	16.8	5854.7 *20*	0.81 *31*	3.4 *5*
5420	2.5	5418.7 *20*	2.4 *5*	1.01 *33*
		5369.9 *30*	0.59 *35*	0.90 *31*
4660	9.1	4661.6 *30*	<0.5	0.54 *38*
4618	4.2	No 4618	<0.5	<0.5
4137	4.2	4133.5 *30*	<0.5	1.4 *5*

[a]Ref. 4. The γ-ray energies have quoted accuracies of ± 3-6 keV.
[b]In our notation, 6580.5 *30* ≡ 6580.5 ± 3.0, etc. The γ-ray energies correspond to thermal neutron capture.
[c]Relative photon intensity based on a value of 100 for the sum of the Ge(Li) detector counts between 2.3 and 3.5 MeV. In our notation, 3.7 *4* ≡ 3.7 ± 0.4, etc.
[d]The 6108.2-keV transition represents a possible transition to the 472.6-keV ($5/2^-$) final state.

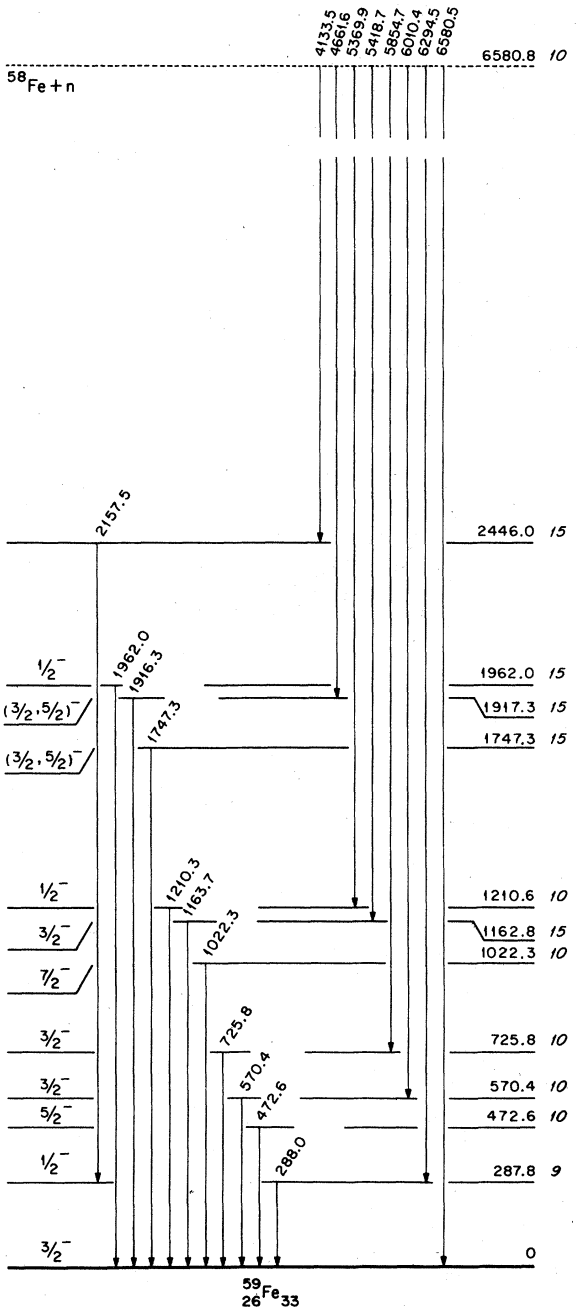

FIG. 3. Level scheme for ^{59}Fe from the present experiment. All energies are in keV. Spins and parities are from Ref. 5. In our notation for level energy, 287.8 *9* ≡ 287.8 ± 0.9, etc.

the 37 γ rays have been incorporated into a level scheme involving 14 excited states. Time-of-flight data obtained with an enriched ^{54}Fe target revealed four resonances. However, no high-energy, primary γ rays were observed from these resonances.

TABLE II. Secondary γ rays from the $^{58}Fe(n,\gamma)$ ^{59}Fe reaction

E_γ (keV)[a]		E_γ (keV)[a]		E_γ (keV)[a]	
288.0	*10*	1402.6[b]	*15*	2779.2[b]	*20*
472.6	*10*	1642.2[b]	*15*	3016.0[b]	*20*
570.4	*10*	1747.3	*15*	3107.7[b]	*20*
725.8	*10*	1916.3	*15*	3185.3[b]	*20*
1022.3	*10*	1962.0	*15*	3359.8[b]	*20*
1163.7	*20*	2157.5	*15*	3410.9[b]	*20*
1210.3	*10*	2702.3[b]	*20*		

[a]In our notation, 288.0 *10* ≡ 288.0 ± 1.0, etc.
[b]Not placed in level scheme.

TABLE III. Energy levels in ^{59}Fe

Other works[a] E_γ (keV)		Present work E_γ (keV)	
0		0.0	
287	*6*	287.8	*9*
473	*6*	472.6	*10*
574	*16*	570.4	*10*
728	*6*	725.8	*10*
1026	*6*	1022.3	*10*
1081	*16*		
1162	*6*	1162.8	*15*
1214	*10*	1210.6	*10*
1517	*10*		
1572	*10*		
1648	*10*		
1749	*10*	1747.3	*15*
1922	*6*	1917.3	*15*
1964	*10*	1962.0	*15*
...		...	
...		...	
2442[b]	*10*	2446.0	*15*
...		...	
...		...	
6582[c]	*3*	6580.8	*10*

[a]Mainly from (d,p), (t,p) - Ref. 3. Above 2 MeV excitation, this column is not complete; see, for example, Ref. 1. In our notation, 287 *6* ≡ 287 ± 6, etc.
[b]From (d,p) - Ref. 1
[c]Neutron separation energy from Ref. 4.

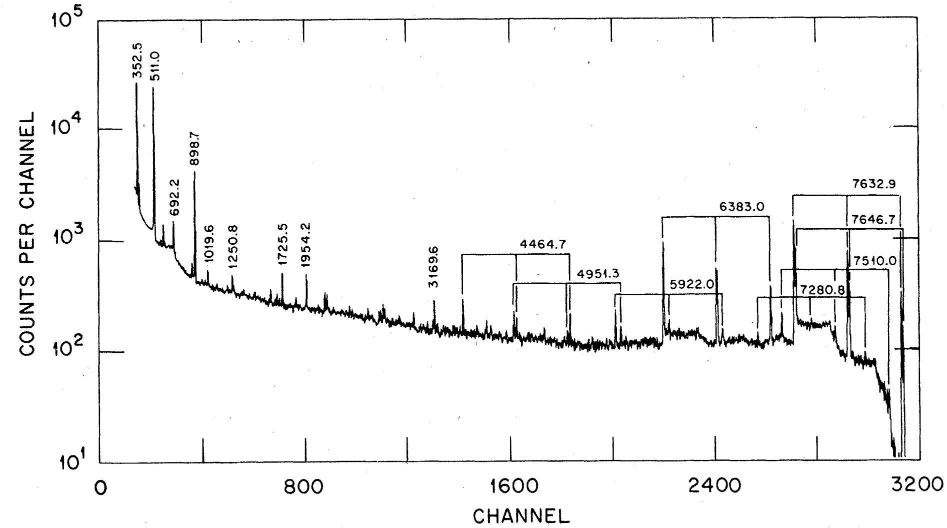

FIG. 4. The γ-ray spectrum (without off-resonance background corrections) from the 1.167-keV neutron resonance in ^{56}Fe. All γ-ray energies are in keV. Only selected peaks are labelled.

II. EXPERIMENTAL PROCEDURE

The Oak Ridge Electron Linear Accelerator (ORELA) facility was used to provide pulsed beams (30-nsec bursts at a pulse repetition rate of 500 Hz or 12-nsec bursts at 800 Hz) of neutrons for capture studies of 40 g, 82% enriched ^{58}Fe; 60 g of natural Fe (91.7% ^{56}Fe); and 27 g, 98% enriched ^{54}Fe. The neutrons were produced by a beam of 140-MeV electrons which were stopped in a water-cooled Ta target. The resulting bremsstrahlung produced neutrons via the (γ,xn) reaction. The neutrons were moderated by a 3.2 cm thick water moderator of 15 cm diameter which surrounded the Ta target. The (n,γ) measurements were carried out at a 10.45 m station. The quoted neutron energies in this paper are considered accurate to ±0.5%. Each sample was placed in the beam for a running time of approximately two weeks with a shielded 37 cm^3 Ge(Li) detector located 20 cm below the sample. The γ-ray intensity values given in this paper are based on data obtained at 90°. Overlap neutrons were suppressed by a ^{10}B filter in the beam. Two stainless steel shadow bars totalling 1.5 m and a Pb filter 5 cm thick were inserted in the beam in order to shield the sample from fast neutrons and from the γ flash.

The Ge(Li) detector was enclosed in a copper screen housing to shield out electromagnetic interference from the accelerator. The detector preamplifier provided both timing and analog signal outputs. The timing of the events was carried out with a filter amplifier and a constant fraction discriminator, and the resulting outputs were transmitted to a data acquisition center. The event times were digitized by a 10-nsec clock. The analog signsls were digitized by a 4096-channel, 100-MHz analog to digital converter. The digitizers were interfaced together so as to maintain correct correlation between times and pulse heights for each event.

III. RESULTS

A. The ^{58}Fe$(n,\gamma)^{59}$Fe reaction

Fig. 1 shows a spectrum of all neutron capture γ-ray events *versus* neutron flight time. Based on these data, appropriate gates were selected both on-resonance and off-resonance. Useful spectroscopic data were obtained only from the 230- and 359-eV resonances (see Fig. 2).

A listing of the primary γ-ray energies and relative intensities is given in Table I. Also shown for comparison are the γ rays from thermal neutron capture.[4] Secondary γ rays are listed in Table II. The level scheme based on the present data is shown in Fig. 3. The energy levels from the present work and those from a recent evaluation[5] are given in Table III. The spin and parity (J^π) assignments are from Ref. 3. The neutron separation energy, S_n, was determined to be 6580.8 ± 1.0 keV.

The 230- and 359-eV resonances are known to be p-wave resonances based on a lack of interference between resonance and potential scattering in the curve of neutron transmission *versus* neutron energy.[7] Therefore, these resonances have $J^\pi = 1/2^-$ or $3/2^-$. Since the seven primary γ rays above 4.5 MeV shown in Fig. 3 lead to $1/2^-$, $3/2^-$ or $5/2^-$ levels, these γ rays are most probably *M1* transitions. The partial radiation widths for these transitions are not known at this time.

In the (n,γ) reaction with low-energy neutrons, the partial radiation widths from adjacent resonances are almost always uncorrelated with each other. However, in a recent study of the ^{35}Cℓ$(n,\gamma)^{36}$Cℓ reaction, Chrien and Kopecký[8] found similar γ-ray spectra from neighboring capture states of opposite parity. Expressed as a linear correlation coefficient, these authors found $r = +0.84\,^{+0.06}_{-0.10}$ for a set of 14 transitions seen in both s-wave thermal capture and p-wave, 398-eV resonance capture in ^{35}Cℓ.

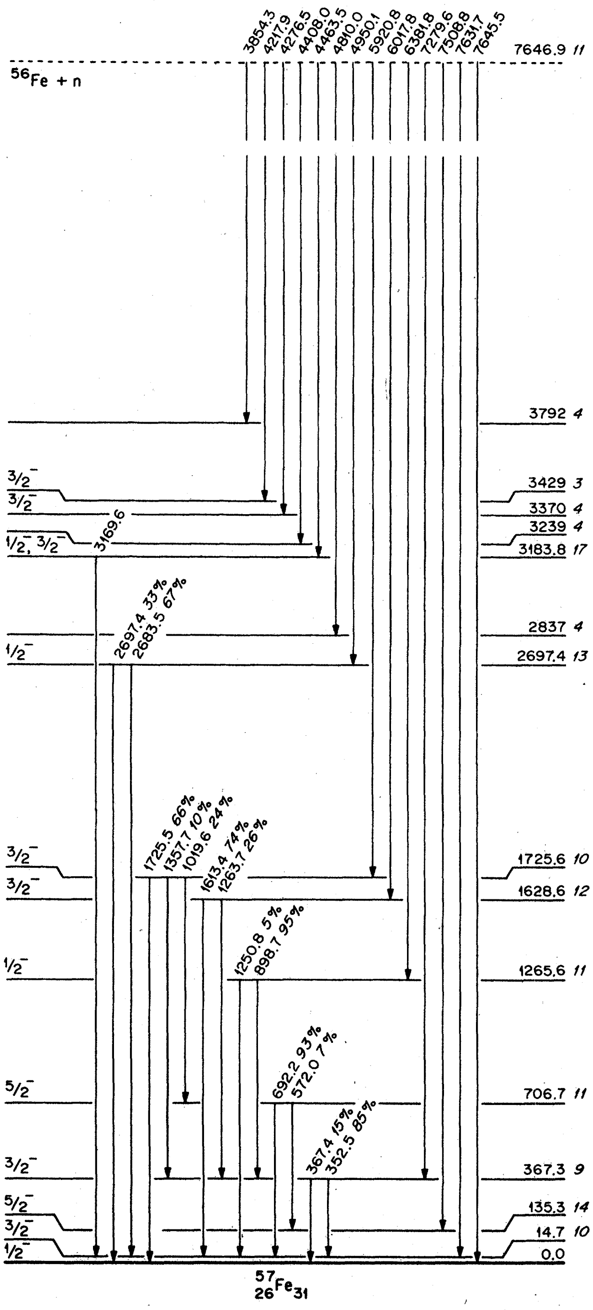

FIG. 5. Level scheme for ^{57}Fe from the present experiment. All energies are in keV. Spins and parities are from Ref. 12. In our notation for level energy, 14.7 *10* ≡ 14.7 ± 1.0, etc.

We have observed a similar *E1* - *M1* role reversal in the case of the $^{58}Fe(n,\gamma)$ reaction. For the nine transitions observed in thermal and resonance capture (see Table I), we obtain $r = +0.77 ^{+0.12}_{-0.22}$, a strong positive correlation, in the case of thermal and 230-eV resonance capture. We also obtain $r = +0.18 ^{+0.35}_{-0.40}$, negligible correlation, in the case of thermal and 359-eV resonance capture. The error limits represent rms errors deduced by the use of Fisher's transformation[9] and reflect the smallness of the sample size. The error due to experimental uncertainties in the intensity values is much smaller and hence not included.

McLean *et al.*[3] have made a detailed comparison between the experimental level scheme (and spectroscopic factors) with those obtained from rotational model calculations.[10,11] They have shown that the experimental data provide strong support for the existence in ^{59}Fe of a rotational band structure. [The ground state, the 473-keV level and the 1022-keV level comprise the $K = 3/2^-$ (312) band, the 288-keV and the 726-keV levels comprise the $K = 1/2^-$ (310) band, etc.].

TABLE IV. Relative photon intensities of the primary γ rays from the $^{56}Fe(n,\gamma)^{57}Fe$ reaction for the neutron resonance at 1.167 keV

Other work[a] E_γ (keV)	I_γ[b]			Present work E_γ (keV)[c]		I_γ[b]	
7645.4	51	*3*		7645.5	*20*	41	*4*
7631.0	100	*4*		7631.7	*20*	100	*4*
7511.4	7.0	*14*		7508.8	*20*	5.2	*8*
7279.2	2.2	*8*		7279.6	*30*	1.9	*7*
6507.0	2.6	*5*	No	6507		<1.0	
6382.2	37	*1*		6381.8	*20*	35	*5*
6020.0	3.6	*8*		6017.8	*30*	1.1	*5*
5922.0	7.8	*11*		5920.8	*30*	5.6	*13*
			No	5193[d]		<1.2	
4950.8	5.9	*10*		4950.1	*20*	5.0	*14*
4811.7	<0.5			4810.0	*30*	1.5	*10*
4676.4[e]	1.5	*6*	No	4676		<1.4	
			No	4589[d]		<1.0	
4463	5.8	*11*		4463.5	*20*	5.5	*10*
4408	1.7	*7*		4408.0	*30*	1.3	*8*
			No	4400[d]		<1.0	
4276.8	1.4	*7*		4276.5	*30*	1.7	*8*
4220.0	1.4	*7*		4217.9	*25*	1.2	*8*
4014.2[e]	<0.5		No	4014		<1.0	
3856.6	1.3	*9*		3854.3	*35*	1.9	*11*

[a]Ref. 6. The energies have quoted accuracies of <1 keV for 6.5 < E_γ <8.0 MeV and <2 keV for E_γ <6.5 MeV, except for the weaker lines.
[b]Relative intensity normalized to 100 for the intensity of the 7631-keV γ ray. In our notation, 51 *3* ≡ 51 ± 3, etc.
[c]In our notation, 7645.5 *20* ≡ 7645.5 ± 2.0, etc. The γ-ray energies correspond to thermal neutron capture.
[d]The 5193-, 4589-, and 4400-keV transitions represent possible transitions to $1/2^+$ final states at 2454-, 3057.6-, and 3247-keV, respectively.
[e]Not primary transitions.

TABLE V. Secondary γ rays from the $^{56}Fe(n,\gamma)^{57}Fe$ reaction

E_γ (keV)^a		E_γ (keV)^a		E_γ (keV)^a	
352.5	*10*	1357.7	*10*	2683.5	*20*
367.4	*10*	1460.3^b	*10*	2697.4	*20*
572.0	*10*	1613.4	*20*	2971.1^b	*20*
692.2	*10*	1672.2^b	*20*	3152.1^b	*20*
898.7	*10*	1725.5	*20*	3169.6	*20*
1019.6	*10*	1954.2^b	*20*	3574.8^b	*20*
1250.8	*10*	2362.4^b	*20*	3666.6^b	*20*
1263.7^c	*20*	2539.3^b	*20*		

^{a}In our notation, 352.5 *10* ≡ 352.5 ± 1.0, etc.
^{b}Not placed in level scheme.
^{c}Probable doublet.

B. The $^{56}Fe(n,\gamma)^{57}Fe$ reaction

Below 20 keV, the only known neutron resonance in ^{56}Fe occurs at 1.167 keV. The γ-ray spectrum from this resonance is shown in Fig. 4. A listing of the primary γ-ray energies and relative intensities is given in Table IV. These are compared with the results obtained by Chrien *et al.*[6] We find good overall agreement. However, we did not observe a γ ray at 6507 keV. Secondary γ rays observed in the present study are listed in Table V. The level scheme based on our data is shown in Fig. 5. The J^π assignments are from the *Nuclear Data Sheets*.[12]

The 1.167 keV resonance has been shown to be a p-wave resonance by transmission[13] and scattering[14] measurements. Furthermore, this resonance has been shown to be $1/2^-$ from angular distribution measurements (90° and 135°) involving the 7645- and 7632-keV transitions.[6] The 135-keV level has a definite $5/2^-$ assignment based on Coulomb excitation and lifetime measurements.[15] Therefore, the 7509-keV primary transition is an *E2* transition. High-energy primary γ transitions in the (n,γ) reactions are predominantly *E1* or *M1*; primary *E2* transitions are extremely rare. The 7509-keV transition in ^{57}Fe joins a select group of eight other transitions which are known to be primary *E2* transitions in the (n,γ) reactions.[16]

A strong correlation exists between the intensities of primary transitions from s-wave, thermal neutron capture[17] and from p-wave, 1.167-keV resonance neutron capture. We obtain $r = +0.84\ ^{+0.06}_{-0.09}$. This remarkable correlation has also been cited in Ref. 8.

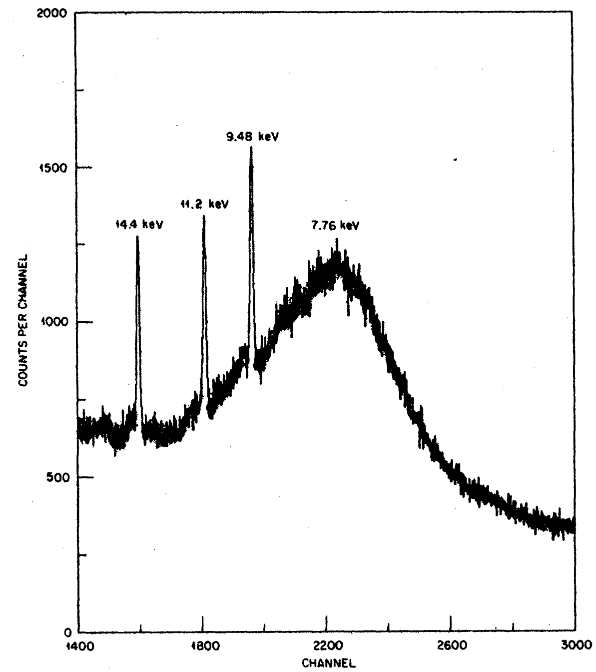

FIG. 6. Counting rate for all γ-ray events above 100 keV *versus* neutron time-of-flight for the enriched ^{54}Fe target. Resonances in ^{54}Fe are identified.

C. The $^{54}Fe(n,\gamma)^{55}Fe$ reaction

An attempt was made to study the $^{54}Fe(n,\gamma)$ reaction. The time-of-flight spectrum is shown in Fig. 6. In a run lasting 2 weeks, the γ-ray spectra (not included here) from the four labelled resonances showed the presence of the 411- and 931-keV transitions known to de-excite the first and second excited states in ^{55}Fe (Ref. 18). However, no high-energy primary γ rays in ^{55}Fe were observed. We ascribe our inability to a combination of factors, including the smallness of our sample, low values for the radiation widths and the fact that the resonances lie at relatively high neutron energies.

IV. ACKNOWLEDGEMENTS

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