(0, 1) 4^+ and (0, 0) 3^+ states in question. These model-supported conjectures are indicated in Fig. 9.

Also indicated in Fig. 9 is the conjecture that the 3.708-MeV level is the 6^+ level of the (3, 0) band. Not indicated is the weaker possibility that the 4.708-MeV level is the 5^+ member of the (0, 0) band. These suppositions are illustrated schematically in the E_J versus $J(J+1)$ plot of Fig. 10. This plot also indicates estimated excitation energies for the 4^- level of the odd-parity band and the 7^+ member of the ground-state band. Clearly, further work is possible and desirable for an understanding of the collective states of mass 22.

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Gamma Rays Following Resonant Neutron Capture in ^{56}Fe†

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The spectrum of γ rays following neutron capture at the 1167-eV resonance in ^{56}Fe has been measured at 90° and 135° to the incident beam. The partial widths for radiative decay have been determined and compared to the Weisskopf estimates. The $M1$ and $E1$ γ-ray strengths are found to be comparable, and a sizable $E2$ γ ray in the resonance has been recorded. On the basis of the γ-ray measurements at two angles, and from what has been determined from other experiments, the spin and parity of the 1167-eV resonance are shown to be $\frac{1}{2}^-$.

THE lowest-energy neutron resonance in ^{56}Fe, located at 1167 eV,[1] has been investigated by means of virtually all the techniques available to slow-neutron spectroscopy. This resonance thus serves as an excellent example of the combining of these techniques to completely determine the parameters of a neutron resonant state. The present paper is a description of a high-resolution γ-ray study of this level recently undertaken at the HFBR fast-chopper time-of-flight facility. The additional information gained by this study has led to a unique spin assignment for this level, as well as a determination of many of its partial radiative widths.

Because of its small neutron width, this resonance was not seen in earlier transmission studies. In 1960, however, Isakov, Popov, and Shapiro[2] reported its detection by measuring the energy dependence of the capture cross section in iron, using a lead "slowing down time" spectrometer. In 1963, Moore, Palevsky, and Chrien[3] determined the neutron and total radiation widths through the use of a self-indication method in conjunction with the Brookhaven National Laboratory–Atomic Energy of Canada, Ltd. Chalk River chopper. They also examined the resonance γ-ray spectrum with a low-resolution NaI detector and reported a qualitative similarity between resonance and thermal capture in ^{56}Fe.

High-resolution transmission data for this resonance were reported by Block[4] in 1964. The symmetry of the transmission dip with respect to its resonant energy led Block to conclude that the level was not due to S-wave neutron capture. Recently, Asami, Moxon, and Stein[5] have examined the scattered neutrons in an energy region containing this level as a function of energy and angle with respect to the incident beam. The appearance of an energy asymmetry in the differential cross section, and the angular behavior of that scattering-cross-section asymmetry enabled them to show that the resonant state is of odd parity.

In an effort to complete the specification of this state, the γ-ray spectra following the capture of neutrons in iron from thermal to $\sim$2 keV have been recorded with the aid of a two-parameter (neutron flight time and γ-ray detector pulse height) recording system and the HFBR fast chopper. A Ge(Li) detector of 4-cm^3 volume and with 0.1% energy resolution was used in the study. The γ-ray energies were measured relative to the ^{54}Cr transition energies[6] and the hydrogen capture line,[7] and are believed to possess an absolute accuracy of better than 1 keV for $6.5 \leq E_\gamma \leq 8.0$ MeV and better than 2 keV for $E_\gamma \leq 6.5$ MeV, except for

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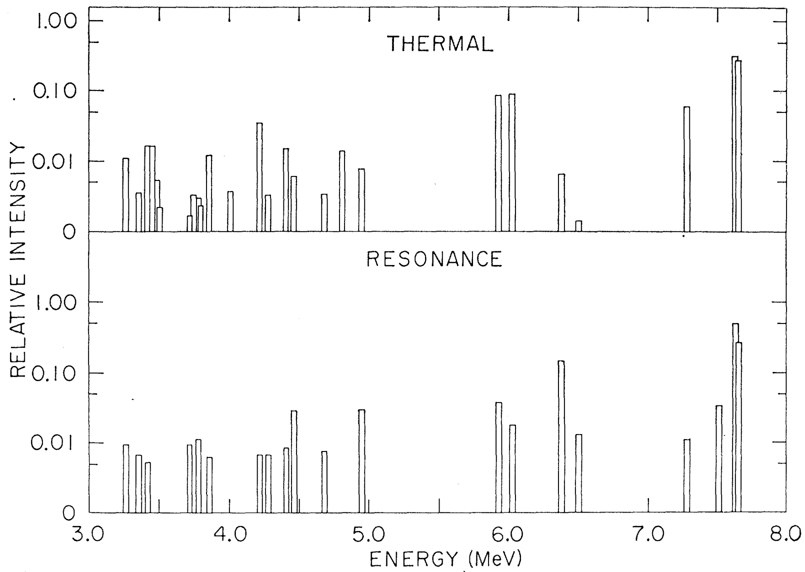

FIG. 1. Comparison of the intensities in the resonance and thermal spectra from an iron target.

the weaker lines in the spectrum. The energy dependence for the transitions in the off-resonance region has been previously reported.[8] The relative intensities in the resonance were determined in the conventional manner, using the absolute intensities recorded for thermal capture by Rasmussen *et al.*[9] The partial widths were calculated assuming the total width of Ref. 3, and they are shown in Table I. A graphical comparison between the thermal and resonance transition strengths is given in Fig. 1, which illustrates the qualitative similarity in the spectra noted in the earlier, low-resolution NaI work. In particular, both spectra are dominated by strong transitions to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ ground and first excited states.

To determine the spin of this resonance, additional data were taken with a 35-cm³ Ge(Li) detector at 90° and 135° to the incident beam with a $\frac{1}{4}$-in. iron sample. The distribution of γ rays resulting from $l\neq 0$ neutron capture is not in general isotropic. The differential cross section is given by Lane and Thomas[10]:

$$\frac{d\sigma}{d\Omega}=\frac{(-1)^{s-s'}}{4k^2(2S+1)}\left[\sum_L\sum_{J,l}\bar{Z}\bar{Z}_1TT^*P_L(\cos\theta)\right],$$

in which $\bar{Z}$ and $\bar{Z}_1$ are the particle and γ-ray coefficients tabulated by Ferguson,[11] and $T\equiv T_{ll'ss'}{}^J$ are the collision matrix coefficients. For an intermediate (resonance) state of definite J, following from the capture of $l=1$ neutrons on a target of spin zero, the above expression simplifies to

$$d\sigma/d\Omega\propto a_0+a_2P_2(\cos\theta).$$

The ratio a_2/a_0 depends on the resonance and the final-state spins J_0 and J_f; in particular, $a_2/a_0=0$ for spin-$\frac{1}{2}$ resonances on account of the triangle condition of (J_0, J_f, L).

TABLE I. Partial radiative widths for capture in the 1167-eV resonance of ^{56}Fe. The energies listed here are for lines seen in either resonance or thermal capture in this experiment. The lines marked with an asterisk are not primary transitions.

E_γ (keV)	Width (meV) $\Gamma_{\gamma i}$
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	76±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

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[9] N. C. Rasmussen, Y. Hukai, Y. Inouye, and V. J. Orphan, Massachusetts Institute of Technology Report No. MIT NE-85 (unpublished).

[10] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).

[11] A. J. Ferguson, *Angular Correlation Methods in Gamma-Ray Spectroscopy* (North-Holland Publishing Co., Amsterdam, 1965).

The strong ground-state transition observed in the 1167-eV resonance clearly implies $J_0 \leq \frac{3}{2}$, ruling out values of $l > 1$. Portions of the γ-ray spectra showing the two escape peaks of transitions feeding the ground state ($\frac{1}{2}^-$) and the 14-keV first excited states ($\frac{3}{2}^-$) of ^{57}Fe are shown in Fig. 2 for the observation angles of 135° and 90°. The ratios of the peaks would be expected to change by about a factor of 2 for a resonance of spin $\frac{3}{2}$. The observed spectra indicate no such variation, implying that $a_2/a_0 = 0$ and $J_0 = \frac{1}{2}$.

The qualitative similarity of the resonance and thermal spectra is somewhat surprising in view of the opposite parity of the capturing states. One notable difference between the spectra is the appearance of a transition to the $\frac{5}{2}^-$ state at 134 keV in the resonance spectrum. The resonance assignment of $\frac{1}{2}^-$ leads us to conclude that this transition is of $E2$ character and represents an enhancement of about 100 over the Weisskopf single-particle estimates, as conventionally applied to neutron capture.[12]

An interesting consequence of the spin and parity assignments and the similarity of the spectra is the near equality of the electric and magnetic dipole transition strengths. Since most of the low-lying ^{57}Fe levels are known to be of odd parity from (d, p) studies, the thermal capture γ rays are predominately electric dipole, as is generally assumed for thermal-neutron capture. In the resonance, however, the predominant deexcitation mode is magnetic dipole. The photon strength functions are defined as follows[12]:

$$k_{E1} = \langle \Gamma_{\gamma i}(E_1) \rangle / E_\gamma^3 A^{2/3} D$$

and

$$k_{M1} = \langle \Gamma_{\gamma i}(M_1) \rangle / E_\gamma^3 D,$$

and they can be evaluated under the reasonably accurate assumption that all of the significant high-energy γ rays following thermal capture are $E1$, while those from resonance capture, with the one exception noted above, are $M1$. The results are

$$k_{E1} = 0.0016, \qquad k_{M1} = 0.033,$$

assuming that $D_{l=0} \approx 10$ keV and $D_{l=1} \approx 3.3$ keV.

A comparison of these numbers indicates the approximate equality for $E1$ and $M1$ transition strengths in ^{57}Fe ($\langle \Gamma_{\gamma i}(E1) \rangle / \langle \Gamma_{\gamma i}(M1) \rangle \approx 2.1$). This point has been recently emphasized by Bollinger[13] in the higher-mass region where $A > 100$. The photon strength functions reported here are in excellent agreement with the results of Bird, Allen, and Kenny,[14] who have measured the spectra following the capture of 10- to 100-keV neutrons in nuclei of mass numbers between 40 and 70.

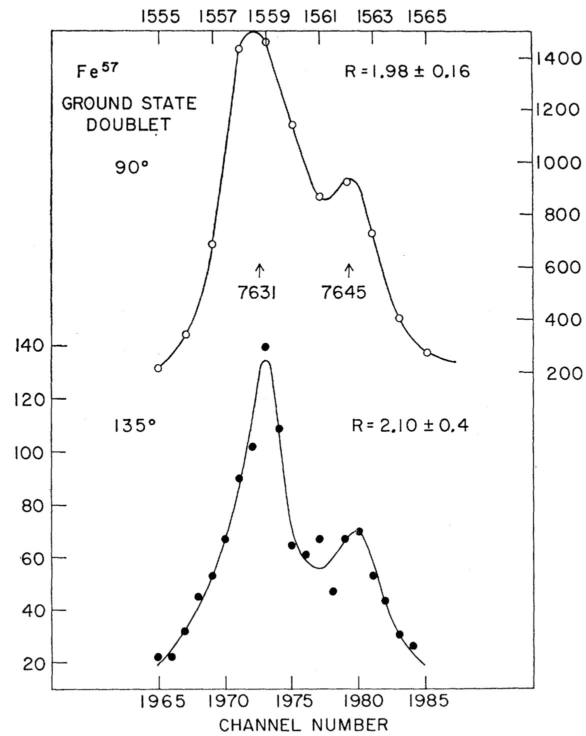

FIG. 2. Transitions to the ground and first excited states of ^{57}Fe observed at 135° and 90°. A $\frac{3}{2}$-spin assignment for the resonance would imply a factor-of-2 change in the relative intensities.

The sizable transition rate for the $E2$ deexcitation observed in the resonance spectrum is within a factor of 4 of the average $M1$ strength, and indicates that it is not in general advisable to assume that dipole transitions account for all of the high-energy capture γ-ray spectrum.

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