Gamma Rays from Fast-Neutron Scattering in ^{54}Fe

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Cross sections for the production of γ rays by the inelastic scattering of neutrons in ^{54}Fe have been measured for incident neutron energies in the range 1.81 to 5.25 MeV_{lab}. γ-ray angular distributions have been measured for γ radiation of sufficient intensity at neutron energies of 1.81 and 4.0 MeV. The angular distributions compare favorably in shape with the theoretical predictions of the Satchler formalism using the neutron penetrabilities of Beyster and of Perey and Buck, but there are small differences in absolute cross sections which can be resolved in part through the incorporation of a correction for Moldauer level-width fluctuations. A multipole amplitude mixing ratio of $0 \leq \delta \leq +2.2$ was determined for the $M1$, $E2$ transition from the 2.961-MeV(2^+) to the 1.409-MeV(2^+) level. Branching ratios for the γ rays stemming from the 2.961-MeV level and the 3.161-MeV level were also determined experimentally.

I. INTRODUCTION

THE measurements and analyses described below were performed at Texas Nuclear Corporation as part of a comprehensive program aimed at providing experimental and theoretical γ-ray production cross sections for a wide variety of elements. It has already been shown that comparison of the γ-ray angular distributions and cross sections with theoretical predictions based on the Satchler formalism[1] can frequently give unambiguous information on the spins of excited nuclear levels and sometimes a strong indication of parity assignment.[2–4] Two critical reviews of this type of analysis have been presented recently by Van Patter[5] and by Sheldon and Van Patter.[6]

Because of the relatively simple shell structure of the ^{54}Fe nucleus, it, together with the other $(1f_{7/2})^n$ nuclei, has been the subject of a number of theoretical studies[7–11] which have tried to predict the locations, spins, and parities of the excited levels. Furthermore, several experimental investigations have been carried out and, through these studies, the low-lying levels have become reasonably well known. The positions of the low-lying excited levels have been well established by the high-resolution (p,p') studies of Aspinall *et al.*[12] and Sperduto and Buechner.[13] Spins and parities have been assigned to some of these levels primarily through the high-energy electron-scattering results of Bellicard and Barreau,[14] the ^{54m}Co decay studies of Sutton *et al.*[15] and Wegener,[16] the (p,p') angular-distribution investigations of Funsten *et al.*[7] and Gray *et al.*,[17] and the $(p,p'\gamma)$ angular-correlation measurements of Thomas *et al.*,[18] Belote *et al.*,[19] and Church *et al.*[20]

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

The experimental equipment and instrumentation used in making the $(n,n'\gamma)$ measurements consisted basically of a pulsed beam, 3.2-MeV Van de Graaff accelerator used in conjunction with neutron time-of-flight electronics and a total absorption γ-ray spectrometer of the type developed by Trail and Raboy.[21] This system has the advantage of permitting the multichannel analyzer to accept data only during the time the γ radiation interacts in the detector, while greatly suppressing the Compton distribution through the use of a large NaI(Tl) anticoincidence mantle. The details and characteristics of this system have been described by Ashe *et al.*[22]

The neutrons of various energies were obtained from both the $^3H(p,n)^3He$ and $^2H(d,n)^3He$ reactions. The

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tritium target consisted of tritium absorbed in a thin ($\sim$1 mg/cm^2) layer of titanium plated on a 10-mil copper disk. The deuterium target consisted of a 1-cm-diam and 1-cm-long cylinder containing deuterium gas at pressures varying from 1 to 3 atm, separated from the vacuum system by a 0.00025-cm nickel foil. The tritium target was used for the 1.81-MeV neutrons and had an energy spread of $\pm$35 keV, while the deuterium cell was used for the remainder of the measurements and gave typical neutron-energy spreads ranging from $\pm$200 keV at 3.25 MeV to $\pm$70 keV at 5.25 MeV.

Neutron flux was monitored with a Hanson-McKibben-type long counter placed at 90° to the charged-particle beam incident on the target and 150 cm from the target. Long-counter backgrounds were determined with a 40-cm-long iron shadow shield placed between the long counter and the target.

The ^{54}Fe scattering sample, a cylinder 2 cm in diameter and 2.07 cm long, was on loan from Oak Ridge National Laboratory, Oak Ridge, Tennessee. The sample weighed 48.36 g and had the following composition: ^{54}Fe, 97.64%; ^{56}Fe, 2.36%; ^{57}Fe, <0.03%; ^{58}Fe, <0.03%. It was placed at 0° to the charged-particle beam incident on the target and from 1 to 5 cm from the target for each measurement except the 3-MeV cross-section measurement. This measurement was taken with the sample placed at 60° to the incident charged-particle beam. The detector, which is mounted on a large rotating arm, was positioned with its face 110 cm from the center of the scattering sample. "Scatterer in" and "scatterer out" runs were made at each energy and angle for a predetermined charge collected at the target. Data were normalized to a standard long-counter count minus long-counter background count at each energy.

A typical γ-ray spectrum for ^{54}Fe taken at an incident neutron energy of 5.25 MeV$_{\text{lab}}$ is depicted in Fig. 1. None of the γ spectra revealed evidence of γ rays from iron isotopes other than ^{54}Fe, except for the 845-keV transition from the first excited state in ^{56}Fe. The original background-subtracted data points have been outlined in heavy lines while the individual γ peaks with their associated one-escape peaks and Compton distributions are indicated with finer lines. These individual peaks have been stripped from the spectrum, using experimental line shapes obtained with standard radioactive γ sources and reaction γ radiation, as described in Ref. 22.

The experimental errors may be separated into two categories. Relative errors are those errors associated with data points in the relative angular distribution. These consist of statistical deviations in the foreground and background runs, estimated errors involved in the stripping procedure, and errors involved in data normalization. The absolute errors, in addition to the above, include errors associated with neutron attenuation and multiple scattering in the scatterer, γ-ray attenuation

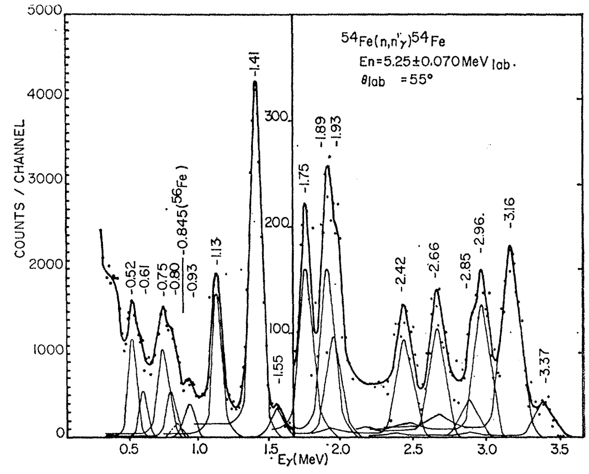

FIG. 1. γ-ray pulse-height spectrum for the ^{54}Fe$(n,n'\gamma)^{54}$Fe reaction at $E_n=5.25$ MeV. The "scatterer out" background has been subtracted. All γ rays indicated are from ^{54}Fe except the 0.845-MeV γ radiation from the first excited level in ^{56}Fe.

and scattering, detector efficiency, and long-counter efficiency. Neutron multiple scattering is estimated to be approximately 3 to 4% based on previous work with ^{56}Fe. Relative errors in the measurements obtained range from 3 to 10%, while the errors in the absolute cross sections range from 17 to 20%.

III. RESULTS AND DISCUSSION

Differential $(n,n'\gamma)$ cross sections have been determined for ^{54}Fe at an angle of 55° to the charged-particle beam incident on the target for laboratory neutron energies ranging from 1.81 to 5.25 MeV. Total cross sections have been calculated from the 55° differential cross sections by multiplying the 55° values by 4π. This is usually reasonable because at 55° the second-order term of the Legendre-polynomial expansion used to describe the γ-ray distributions is essentially zero and the higher-order terms are generally small; thus, the P_0 term is dominant at 55° and the cross section at this angle is representative of the total cross section. A problem arises, however, in dealing with $2^+(E2)0^+$ or $3^-(E3)0^+$ transitions near threshold, for in both cases the higher-order terms are then not negligible and can lead to errors in the total cross section amounting to as much as $\sim$14% (cf. p. 157 of Ref. 6, where the question of limiting angular distributions is discussed). In the present case the maximum possible error in total cross section for the $2^+(E2)0^+$ transitions near threshold is about 8%. The procedure described above was adopted, therefore, in view of the fact that angular distributions were not measured at each energy. Total cross sections determined in this manner are tabulated with the measured 55° differential cross sections in Table I.

The γ rays which appear in Fig. 1 and whose cross sections are tabulated in Table I can, for the most

TABLE I. Experimental $(n,n'\gamma)$ cross sections for pure ^{54}Fe ($d\sigma/d\Omega$ at 55° in mb/sr and σ in mb, ±20%).

Level of origin (MeV)	γ energy (MeV)	Cross section	$E_{n(\mathrm{lab})}$[MeV] 1.81	3.00	3.25	3.50	3.75	4.00	4.10	5.00	5.25
1.408	1.41	$d\sigma/d\Omega$	34.7	62.6	54.0	59.9	60.8	65.3	68.9	67.5	80.3
		σ	436	786	679	753	764	820	866	848	1009
2.540	1.13	$d\sigma/d\Omega$	···	10.8	10.9	14.9	15.8	20.4	21.0	23.5	27.2
Triple		σ	···	135	137	187	199	256	265	295	342
2.961	1.55	$d\sigma/d\Omega$	···	···	2.7	5.0	5.6	9.8	8.2	8.2	6.9
		σ	···	···	34	63	71	123	103	103	87
	2.96	$d\sigma/d\Omega$		···	4.6	5.8	7.8	7.8	7.7	6.9	5.6
		σ		···	57	73	98	98	96	86	70
3.161	1.75	$d\sigma/d\Omega$		···	···	(1.6)[a]	2.1	2.2	2.4	4.0[b]	4.1[b]
		σ		···	···	(20)	26	28	31	50	52
	3.16	$d\sigma/d\Omega$			···	5.5	7.2	7.4	8.2	7.6	8.3
		σ			···	70	90	94	103	96	104
3.291	1.88+	$d\sigma/d\Omega$			···	···	3.3	3.2	4.6	5.8	7.1
3.340	1.93	σ			···	···	41	40	57	72	89
	0.75	$d\sigma/d\Omega$				···	[<4][c]	[<4]	[<4]	[10.4]	[13.9]
		σ				···	[<50]	[<50]	[<50]	[131]	[175]
	0.80	$d\sigma/d\Omega$				···	[<2]	[<2]	[<2]	[5.9]	[6.7]
		σ				···	[<25]	[<25]	[<25]	[74]	[84]
3.829	2.42	$d\sigma/d\Omega$				···	···	···	···	3.1	4.0
		σ				···	···	···	···	39	51
4.070	2.66	$d\sigma/d\Omega$							···	6.2	4.6
Triple		σ							···	78	57
4.270	2.87	$d\sigma/d\Omega$							···	(1.8)	(1.6)
Double		σ							···	(22)	(20)
4.781	3.37	$d\sigma/d\Omega$								···	1.8
		σ								···	22
4.070[d]	0.92+	$d\sigma/d\Omega$							···	(3.9)	(4.9)
4.270	0.94	σ							···	(49)	(62)
4.700[d]	0.61	$d\sigma/d\Omega$							···	(6.1)	(4.9)
		σ							···	(77)	(62)
3.829[d]	0.52	$d\sigma/d\Omega$					···	···	···	e	(10.0)
4.579		σ					···	···	···		(126)

[a] ( ) γ's distinct but statistics poor.
[b] May include contributions from the 4.270-MeV doublet and/or the 4.700-MeV level.
[c] [ ] Cross sections should be treated as estimates because of γ stripping difficulty.
[d] Level of origin assignments are tentative.
[e] γ present, but cross section not determined because of background difficulty.

part, be fitted without ambiguity into the energy-level scheme of Fig. 2, which was determined from the high-resolution (p,p') measurements.[12,13] The level energies in Fig. 2 are those due to Aspinall *et al.*[12], except for the 2.948-MeV level, which is from Wegener.[16] The spins and parities are a composite of the work of others and the results of this experiment, and are discussed in detail below (under their appropriate level of origin). Excitation curves for some of these γ rays are shown in Fig. 3 together with visual fits to the data points. The error bars shown with these curves represent the total cross-section errors as described earlier.

The theoretical γ-ray angular distribution and cross-section data for comparison with the experimental results have been obtained from the Satchler formalism[1,6] using the Fortran program TRANSEC[23] and the Algol code MANDY,[24] which has recently been extended to permute level spins and to calculate the δ ellipses for multiple mixing automatically. The theoretical differential cross sections are of the form

$$\frac{d\sigma}{d\Omega}=\frac{\lambda\!\!\!^{-2}}{4(2J_0+1)(2s_i+1)}\sum_\nu A_\nu P_\nu(\cos\theta)\,, \qquad (1)$$

where $\lambda\!\!\!^{-}$ is the rationalized wavelength of the incident particle in the c.m. system, J_0 is the ground-state spin of the target nucleus, s_i is the spin of the incident particle, the A_ν are Racah-algebraic weighting constants, and the P_ν are Legendre polynomials of order ν, where ν is a running index prescribed by vector momentum coupling conditions. The spins and parities of the excited levels and the γ-ray branching ratios

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[24] Eric Sheldon and Peter Gantenbein, Z. Angew. Math. Phys. **18**, 397 (1967).

which were used in the calculations are shown in Fig. 2 and discussed in more detail under their appropriate level. The theoretical distributions and cross sections have been calculated with the inclusion of cascade contributions from higher levels. The neutron penetrabilities used for the calculations were those of Beyster *et al.*[25] (for iron) and those of Perey and Buck[26] (for $A=54$). The Beyster penetrabilities stem from a local potential which included no spin-orbit term, while the Perey and Buck penetrabilities were determined from a nonlocal universal potential which included a local spin-orbit term. Theoretical curves were calculated using incoming orbital angular momenta $l_1 \leq 4$ and outgoing orbital momenta $l_2 \leq 3$. The inclusion of spin-orbit considerations in the Perey and Buck penetrabilities was found to yield results indistinguishable from those with spin-orbit coupling omitted.

For γ-ray transitions of mixed multipolarity the multipole amplitude mixing ratio δ is defined by[6,27]

$$\delta = \frac{(J_3 \| L+1 \| J_2)}{(J_3 \| L \| J_2)} = \pm \left(\frac{I_{L+1}}{I_L} \right)^{1/2}, \tag{2}$$

where J_2 is the spin of the excited intermediate level, J_3 is the spin of the final level, L is the lowest-order permitted multipole possible for the transition, and I is the intensity of the indicated multipole transition.

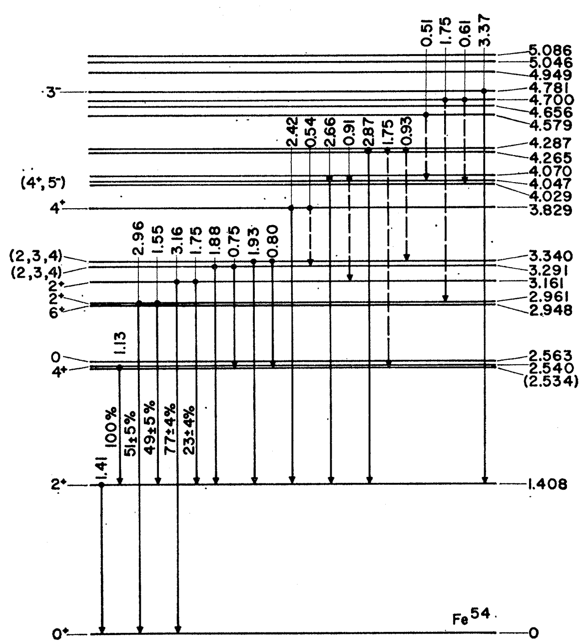

FIG. 2. Energy-level diagram and decay scheme for ^{54}Fe. Solid lines indicate transitions with definite assignments, while dashed lines indicate transitions with tentative assignments.

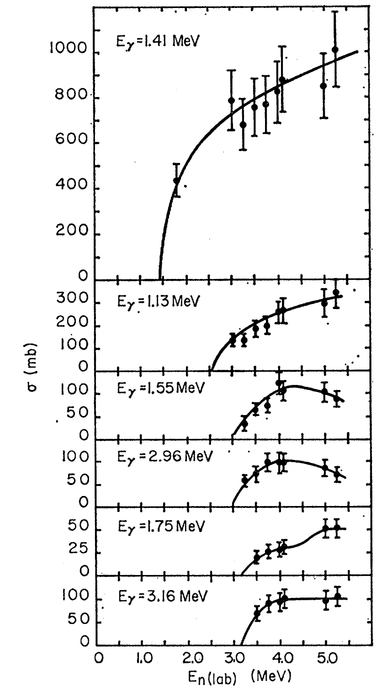

FIG. 3. Excitation curves for six γ transitions in ^{54}Fe. Solid curves are visual fits to the data points. Error bars indicate total errors.

Comparison of the theoretical and experimental angular distributions are shown both on relative and on differential cross section scales in Figs. 4, 5, and 6. The relative errors are depicted in Figs 4, 5, and 6 by the solid portion of the error bars while the errors in the differential cross-section values are indicated by the dashed portion of the error bars in Figs. 5 and 6. The theoretical curves shown in Fig. 4 have been calculated using the Beyster penetrabilities, but the shape predictions are virtually identical for both sets of penetrabilities. The cross-section predictions, on the other hand, are usually substantially different, as can be seen from Figs. 5 and 6.

A discussion of the results obtained for each level is given below, with the spin and parity assignments (if any). A tabulation of spin and parity assignments appears in Table II.

A. The 1.409-MeV Level (2^+), $E_\gamma = 1.41$ MeV

The spin and parity of the 1.409-MeV level have been well established. The decay of this level to the ground state (0^+) can proceed only by the emission of pure $E2$ radiation. Relative, as well as absolute, angular distributions for this γ radiation at incident neutron energies of 1.81 and 4.0 MeV are displayed in Figs. 4, 5, and 6. The anisotropy of the 1.41-MeV γ radiation at a neutron energy of 1.81 MeV is nearly 2, the

[25] J. R. Beyster, R. G. Schrandt, M. Walt, and E. W. Salmi, Los Alamos Scientific Laboratory Report No. 2099, 1957 (unpublished).

[26] E. H. Auerbach and F. G. J. Perey, Brookhaven National Laboratory Report No. 765, 1962 (unpublished).

[27] Mitsuo Sakai and Toshimitsu Yamazaki, Institute for Nuclear Study of the University of Tokyo Report No. INSJ-66, 1964 (unpublished).

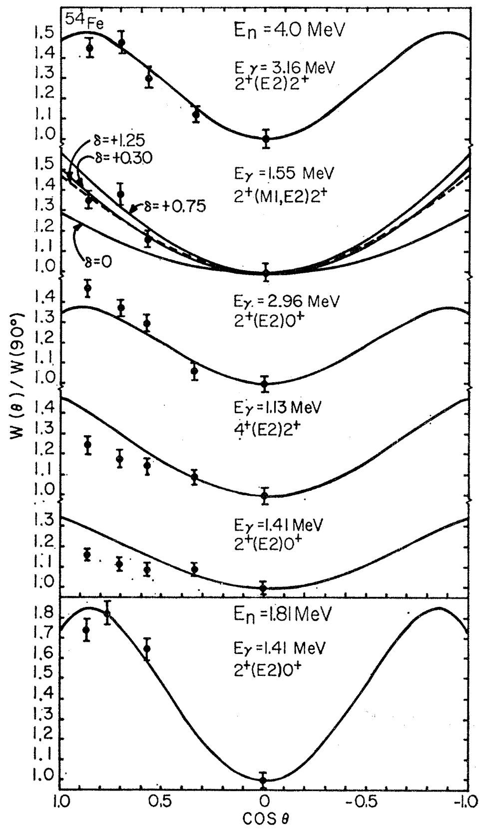

FIG. 4. Relative γ-ray angular distributions for ^{54}Fe. Error bars shown represent relative errors (see text). Curves are theoretical predictions of the Satchler formalism with Beyster penetrabilities.

theoretical limiting value which would be reached just above threshold.[5,6] The angular distribution at 1.81 MeV evinces good structural agreement, but the theoretically predicted cross sections are much too high. The extreme discrepancy in the cross section may well be due to the level-width-fluctuation effect discussed

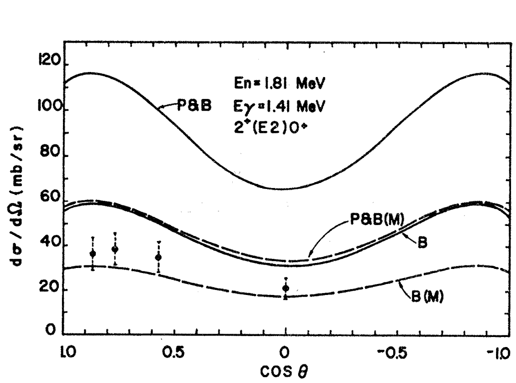

FIG. 5. Angular distribution of the 1.41-MeV γ ray at an incident neutron energy of 1.81 MeV. Relative errors are roughly the same size as the data points and absolute errors are indicated by the dashed error bars (see text). Curves are Satchler predictions with Beyster (B) and Perey-Buck (P & B) penetrabilities. The dashed curves were hand-calculated using the Moldauer modifications (see text).

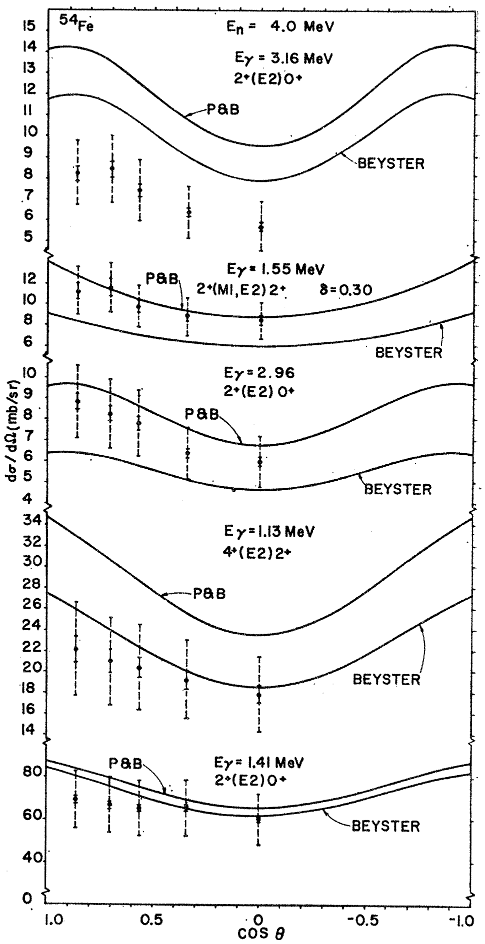

FIG. 6. Angular distributions for γ rays from ^{54}Fe at an incident neutron energy of 4.0 MeV. Relative errors are indicated by the solid portion of the error bars while absolute errors are indicated by the dashed portions (see text). Curves are Satchler predictions with Beyster and Perey-Buck (P & B) penetrabilities.

by Moldauer.[28] Since the effect is expected to show up principally near threshold, diminishing as the incident neutron energy and the number of additional outgoing channels increases, hand calculations were carried out at the lowest incident energy to establish the magnitude and resultant angular distributions. The results, using the two-channel approximation with the expressions and graphs given by Moldauer,[29–31] indicated that the cross-section predictions for the 1.41-MeV γ ray at an incident neutron energy of 1.81 MeV are reduced to considerably nearer the experimental value, and the angular distribution structure is not changed drastically. The results of these calculations are shown in Fig. 5. Similar estimates, however, would not be expected to be valid at higher energies,[28] e.g., 4 MeV. The hand-

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[29] P. A. Moldauer, Phys. Rev. **123**, 968 (1961).
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[31] P. A. Moldauer, Phys. Rev. **135**, B642 (1964).

calculated values are in essential agreement with the initial results of a recent modification by Sheldon of his computer program MANDY to include the Moldauer modifications.

B. The 2.540-MeV Triplet (4^+,0), $E_\gamma = 1.13$ MeV

A triplet has been reported in the vicinity of 2.540 MeV[12,13,19] and assignments have been made for two of the levels, i.e., 4^+ for the 2.540-MeV level[7,15–17] and 0 for the 2.563-MeV level.[19,20] A 1.13-MeV transition to the first excited state was observed in the present work, apparently coming from the 2.534- to 2.540-MeV region though a small admixture from the 2.563-MeV level could have been present. γ-ray angular distributions at an incident neutron energy of 4.0 MeV are shown in Figs. 4 and 6 for the 1.13-MeV radiation. A 4^+ assignment to a single level at 2.540 MeV gives the best fit as regards angular distribution shape and cross section, though the theoretically predicted anisotropy is considerably higher than the experimental value. This may well be due to small contributions from the 2.563-MeV, spin-zero level reported by Belote *et al.*[19] and Church *et al.*,[20] since the isotropic contribution from a $0^+(E2)2^+$ transition would reduce the predicted anisotropy. The 2.540-MeV triplet has also presented difficulties in the interpretation of the (p,p') angular-distribution measurements by Gray *et al.*,[17] who found that the (p,p') cross section did not drop beyond 90° as predicted by their distorted-wave Born-approximation (DWBA) calculations and as they observed for single comparable 4^+ levels in neighboring nuclei. The assignment of 4^+ to a level at about 2.540 MeV is, furthermore, in excellent agreement with recent ^{54m}Co decay measurements of Wegener,[16] who made an assignment of 4^+ to a level at 2537 ± 2 keV.

C. The 2.961-MeV Level (2^+), $E_\gamma = 1.55$, 2.96 MeV

The spin and parity of the 2.961-MeV level have been well established as 2^+,[7,14,17] although this assignment was in direct contradiction to an earlier radioactivity assignment of 5^- or 6^+ by Sutton *et al.*[15] The ^{54m}Co decay has recently been remeasured by Wegener,[16] using a Ge-Li detector, and an assignment of 6^+ made to a level at 2948 ± 3 keV. Thus, there is clearly a doublet in this region with assignments of 2^+ and 6^+ and a separation of about 10 keV. In the present work two γ transitions were observed from the 2.961-MeV level: a 1.55-MeV transition to the first excited state (2^+) and a 2.96-MeV ground-state transition, with the 1.55-MeV transition having a branching ratio of $(49 \pm 5)\%$. This branching ratio does not compare favorably with the value of $(37 \pm 5)\%$ obtained by Thomas *et al.*[15]

The ground-state transition demonstrates the typical $2^+(E2)0^+$ angular distribution as shown in Figs. 4 and 6. The 1.55-MeV transition is an $M1$, $E2$ mixture and in Fig. 4 the experimental angular distribution is compared with theoretical curves calculated for several of the possible δ values. The multipole ellipse method described by Sheldon and Van Patter[6] indicated δ to lie within the range $0 \leq \delta \leq +2.2$, in good agreement with the value of $\delta = +0.25 \pm 0.19$ determined by Thomas *et al.*[18]

TABLE II. Spin and parity assignments to excited levels in ^{54}Fe. Parentheses indicate tentative or questionable assignments.

Excited level	Spin and parity assignments (a)	(b)	(c)	(d)	(e)	(f)	(g)
1.409	2^+	2^+	2^+	2^+	2^+		2^+
(2.534)							
2.540		4^+	} 4^{+h}	} $(4^+)^h$			4^+
2.563						0	
2.961	2^+		2^+	2^+	$2^{(+)}$		2^+
2.948		6^+					
3.161			2^+	2^+	$2^{(+)}$		2^+
3.291					(2, 3, 4)		(2, 3, 4)
3.340					(2, 3, 4)		(2, 3, 4)
3.829				4^+	$4^{(+)}$		
4.029							
4.047	} $(4^+, 5^-)^h$			(5^-)			
4.070							
4.781	3^-		(3^-)	3^-			

[a] 150-MeV electron scattering (Ref. 14).
[b] Radioactive decay (Refs. 15 and 16).
[c] 17.45 MeV (p,p') (Ref. 7).
[d] 17.9 MeV (p,p') (Ref. 17).
[e] $(p,p'\gamma)$ angular correlations (Ref. 18).
[f] $(p,p'\gamma)$ angular correlations (Refs. 19 and 20).
[g] Present results.
[h] The measurements indicate one level in the bracketed region, but do not specify which particular level.

In discussing systematics of the absolute values of $E2$, $M1$ amplitude mixing ratios for the decay of the second 2^+ state to the first 2^+ state in even-A nuclei, Potnis and Rao[32] showed that the single-particle estimate of the mixing ratio is approached as the neutron number approaches a magic number. The absolute value for the $E2$, $M1$ amplitude mixing ratio of this transition in ^{54}Fe should, therefore, lie between the single-particle estimate ($|\delta| \leq 0.05$)[32] and the mixing ratio for the comparable transition in ^{56}Fe $(0.15 \leq |\delta| \leq 0.20)$.[33] The positive part of this range falls within the data of Thomas *et al.*[18] and the results of the present work. The angular distribution of the 1.55-MeV transition on a differential cross-section scale is shown in Fig. 6, with theoretical distributions for $\delta = 0.30$. The two transitions from the 2.961-MeV level are well described by the theory both as to angular distribution structure and absolute magnitude.

D. The 3.161-MeV Level (2^+), $E_\gamma = 1.75$, 3.16 MeV

The spin and parity of the 3.161-MeV level have also been well established as 2^+.[7,17] Two γ transitions de-

[32] V. R. Potnis and G. N. Rao, Nucl. Phys. **42**, 620 (1963).
[33] *Nuclear Data Sheets*, compiled by K. Way, *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1959), NRC 59-4-54.

excite this level, the 1.75-MeV transition to the first excited state and the 3.16-MeV ground-state transition. The cross section for the 1.75-MeV transition was too small for reliable angular-distribution measurements to be taken, but dependable values for the cross section at $\theta = 55°$ were obtained. The branching ratio for the 1.75-MeV γ ray was $(23\pm4)\%$, which is in reasonable agreement with the value of $(17\pm5)\%$ determined by Thomas *et al.*[18] The branching ratio for this γ ray remains constant up to the 5.0-MeV, where it changes to $(34\pm3)\%$. The increase is evidently due to a contribution from the 4.270-MeV doublet and/or the 4.700-MeV level, both of which could decay by a 1.75-MeV transition.

The angular distribution for the 3.16-MeV ground-state transition is shown in Figs. 4 and 6. The structural fit is admirable, but the predicted cross sections lie somewhat low.

E. The 3.340- and 3.291-MeV Levels, $E_\gamma = 0.75$, 0.80, 1.89, 1.93 MeV

These two levels are, unfortunately, spaced too closely for adequate resolution with a NaI(Tl) detector. All γ rays were definitely present, however, and the close-in run at 5.25 MeV (see Fig. 1) clearly indicated the presence of both the 1.89- and 1.93-MeV transitions as well as the 0.75- and 0.80-MeV γ rays. The 0.80-MeV γ ray also had a substantial contribution from the 0.845-MeV γ ray from the first excited state in ^{56}Fe. It was possible to subtract this contribution using $^{56}\mathrm{Fe}(n,n'\gamma)$ cross sections determined earlier[4] and thereby obtain reasonable estimates of the 0.75- and 0.80-MeV γ-ray cross sections. These are given in Table I. It was difficult to separate the 1.93- and 1.89-MeV γ rays with confidence except in the case of the 5.25-MeV data. At lower energies, e.g., at 4.0 MeV, the 1.93-MeV transition was clearly dominant, but at an incident neutron energy of 5.25 MeV the estimated cross sections for the two transitions are: 1.89 MeV–4.4 mb/sr at 55°, 1.93 MeV–2.7 mb/sr at 55°. Since each of these two levels decays to both a 2^+ and a 4^+ level, their spins must be restricted to 2, 3, or 4.

F. The 3.829-MeV Level (4^+), $E_\gamma = 2.42$ (0.54) MeV

The spin and parity of this level have been assigned as 4^+.[17,18] Two γ transitions were observed from the 3.829-MeV level: a 2.42-MeV transition to the first excited state (2^+) and a probable 0.54-MeV transition to the 3.291-MeV level. There was no evidence of a 1.29-MeV transition to the 2.54-MeV second excited state as reported by Thomas *et al.*[18]

G. Higher Levels

Several γ rays were observed which originated above the 3.829-MeV level. Definite level assignments were possible for the 2.66-, 2.87-, and 3.37-MeV γ rays, which all proceeded to the first excited level, as shown in Fig. 2. The dashed lines in Fig. 2 indicate probable assignments for lower-energy γ rays originating at higher levels. Cross sections for these γ rays are listed in Table II.

Note added in proof. In connection with our discussion of the influence of the Moldauer modification we would draw attention to the results of an extensive set of computations on ^{48}Ti and ^{56}Fe recently completed by E. Sheldon (unpublished) which showed the correction to have *appreciable effect even at energies relatively far above threshold*: Though the discrepancy between "corrected" and "uncorrected" differential cross sections diminished gradually with increasing energy, it nevertheless persisted even at elevated energies. A slight, but perceptible, energy-dependent effect upon the distribution structure was also evident.

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