Decays of the $f_{7/2}$ isomers $^{53}Fe^{g}$ and $^{53}Fe^{m}$

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The decays of 8.5-min $^{53}Fe^{g}$ and 2.5-min $^{53}Fe^{m}$ have been studied with a variety of γ and β^+ detectors in many different singles and coincidence configurations. States in ^{53}Mn populated by $^{53}Fe^{g}$ decay were found to lie at 0 ($J^\pi=\frac{7}{2}^-$), 377.9 ($\frac{5}{2}^-$), 1288.0 ($\frac{3}{2}^-$), 1619.9 ($\frac{9}{2}^-$), 2273.5 ($\frac{5}{2}^-$), 2685.6 ($\frac{7}{2}^-$), 2946.6 ($\frac{9}{2}^-$), 3126.7 ($\frac{9}{2}^-$, $\frac{7}{2}^-$, $\frac{5}{2}^-$), and 3248.0 keV ($[\frac{9}{2}]^-$). States in ^{53}Fe populated by 3040.6-keV ($\frac{19}{2}^-$) $^{53}Fe^{m}$ decay were confirmed at 0 ($\frac{7}{2}^-$), 1328.1 ($\frac{9}{2}^-$), and 2339.6 keV ($\frac{11}{2}^-$). In addition, a 3040.6-keV $E6$ and a 1712.6-keV $M5$ transition were found to compete with the 701.1-keV $E4$ isomeric transition in deexciting ^{53}Fe, this being the first observation of such high multipolarities. The $E6$ has an intensity of 6.0×10^{-4} and the $M5$ an intensity of 1.3×10^{-2} relative to the $E4$ transition. The $E4$, $M5$, and $E6$ transitions are retarded by respective factors of 7.6, 4.2, and 4.3 with respect to single-particle estimates and by somewhat larger factors with respect to simple shell-model estimates.

[RADIOACTIVITY $^{53}Fe^{g,m}$ [from ^{53}Mn(p, $3n$)]; measured E_γ, I_γ, γ-γ coin, E_{β^+}, I_{β^+}, γ-β^+ coin; calculated logft; ^{53}Fe, ^{53}Mn deduced levels J^π; calculated shell-model wave functions, γ transition probabilities.]

I. PREAMBLE

^{53}Fe, an 8.5-min nuclide, which decays primarily by β^+ emission but with some electron capture (ϵ), was first produced in 1936 by an (α, n) reaction on naturally occurring chromium.[1] However, the γ-ray activity associated with the decay of ^{53}Fe was not reported until 1953.[2] Other than the work of Juliano *et al.*[3] in 1959, very little has been done to ascertain the states in ^{53}Mn populated by the decay of ^{53}Fe. The bulk of the available knowledge concerning the states in ^{53}Mn has been obtained via in-beam γ-ray and transfer-reaction studies. Many different groups have performed such studies, but a representative sampling should include recent work on ^{52}Cr(p, γ),[4,5] ^{53}Cr(p, $n\gamma$),[6,7] ^{50}Cr(α, $p\gamma$),[8] ^{53}Cr(p, n),[9] ^{56}Fe(p, α),[10] ^{52}Cr(τ, d),[11] and ^{52}Cr(α, t)[12] reactions—in these papers one can find references to other and older work.

Knowledge of the ^{53}Mn level scheme is important not just for its own sake, but because it promises to be a good test of the validity of simple shell-model calculations. The $N=28$ closed shell is particularly stable and is less subject to configuration mixing than $N=20$.[13] Thus, the ^{53}Mn nucleus with 28 neutrons and 25 protons provides an excellent example for study of the simple $(1f_{7/2})^{-3}$ proton configuration.

During the course of this investigation, a shorter-lived species was observed and subsequently attributed to a metastable isomer in ^{53}Fe.[14] This isomer has a half-life of 2.5 min and an excitation energy of 3040.6 keV.[14-17] It has been interpreted, primarily through isomer preparation ratios[15] and the reduced transition probability of the isomeric transition (apparently of $E4$ multipolarity), as having a spin and parity of $\frac{19}{2}^-$. This corresponds to the highest spin state that can result from the three-quasiparticle configuration $[(\pi f_{7/2})^{-2}]_{6^+}(\nu f_{7/2})^{-1}$.

In this work we report the results of our γ and β^+ studies on these isomers. With the aid of Ge(Li) detectors in various singles and coincidence configurations and with repeated bombardments, many new weak γ rays have been observed. Careful examination of the γ rays deexciting the $\frac{19}{2}^-$ metastable state has resulted in the direct observation of transitions of $E6$ and $M5$ multipolarities.

The measured strengths of these transitions yield an interesting test of simple shell-model assumptions because of the presumed purity of the wave function of the $\frac{19}{2}^-$ state. In a complementary vein, the observed rates constitute a major portion of the little experimental knowledge that is available for such high-multipolarity electromagnetic transitions.

II. SOURCE PREPARATION

$^{53}Fe^{m}$ and $^{53}Fe^{g}$ sources were prepared by the ^{55}Mn(p, $3n$)^{53}Fe reaction, a clean and relatively unexplored method of production, having a calculated Q value of -23.9 MeV.[18] Proton beams having an energy of 34 MeV (the threshold for the production of ^{52}Fe) from the Michigan State University sector-focused cyclotron were used initially to bombard powdered maganese metal (99.94%) targets contained in thin aluminum packets. For the production of the $^{53}Fe^{g}$, 0.5-g targets typically were bombarded with a 2-μA beam of 34-MeV protons for 3 min. However, for production of the metastable isomer $^{53}Fe^{g}$, a 2-μA beam of 40-MeV protons was utilized for 0.5–1.0 min per bombardment.

To expedite handling of the short-lived activities, a pneumatic rabbit system[19] was used to transport targets from the beam to the counting area with a transit time of ≈2 sec. For experiments in which a chemical separation was not necessary, transfer of the powder to a plastic counting vial was accomplished merely by punching a hole in the aluminum packet while still attached to the rabbit and draining the radioactive material directly into the vial. Thus, the total elapsed time between the end of a bombardment and the beginning of counting was typically ≈10 sec for most experiments. In some early experiments and also in later ones which emphasized the $^{53}Fe^{g}$ activity ($t_{1/2} = 8.5$ min), a more leisurely transfer was made, such that the total time required was 3 min. In many experiments a simple but effective chemical separation was carried out after each bombardment in order to remove unwanted contaminants and insure that only Fe was being counted. In this procedure the target was dissolved in 8.0 N HCl and the iron was extracted with isopropyl ether. After being washed with acid, the iron was back-extracted with distilled water and a portion of this was used for counting. This separation generally required about 4 min per bombardment. For positron studies a small portion of the resulting aqueous solution containing the separated iron was dried carefully on a thin foil holder and then counted with appropriate detectors. Since most counting periods were for roughly 24 hours, multiple bombardments and separations were performed, material from each bombardment being counted 2 to 15 min, depending on the experiment.

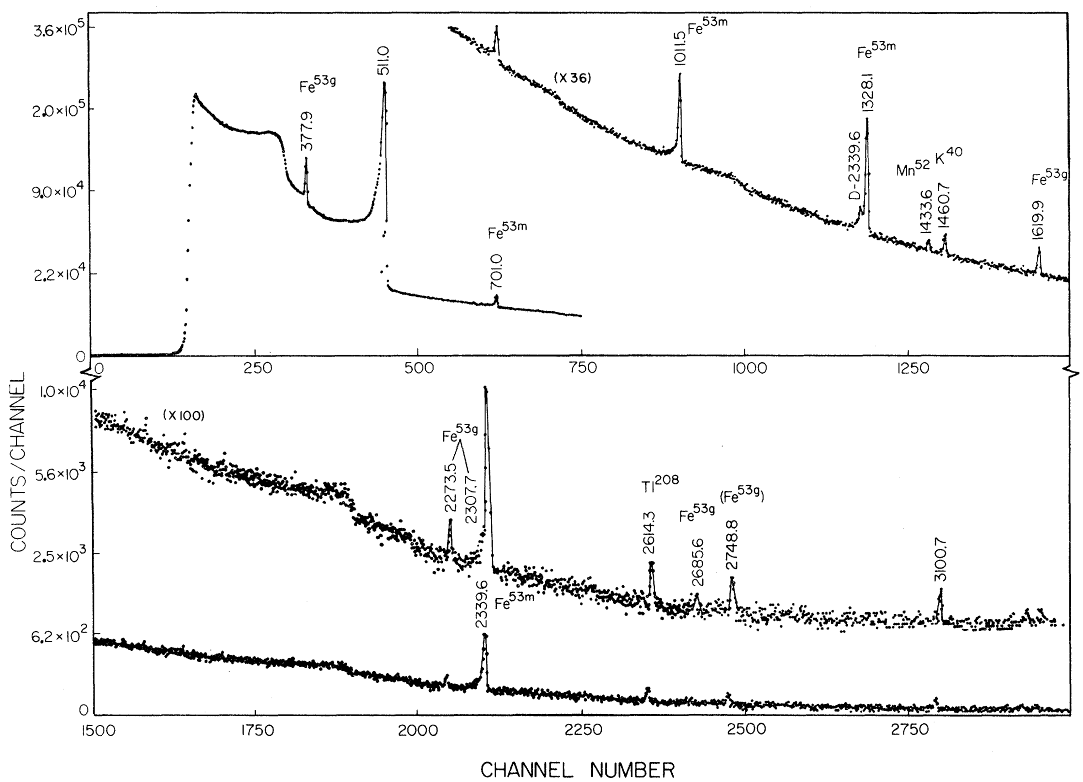

FIG. 1. Singles γ-ray spectrum of $^{53}Fe^{g+m}$ taken with a 2.5% efficient Ge(Li) detector under conditions to optimize the $^{53}Fe^{g}$ γ rays.

III. γ-RAY EXPERIMENTAL DATA

A. ^{53}Fe γ-ray singles spectra

Although many different Ge(Li) detectors were used to obtain the $^{53}Fe^{m+g}$ γ-ray spectra in this study, three were employed most often. Early studies utilized a 7-cm^3 active-volume five-sided coaxial detector [≈0.5% efficient for the ^{60}Co 1332-keV γ, compared to a 7.6×7.6-cm NaI(Tl) detector at 25 cm], which had a resolution of 2.9 keV full width at half-maximum (FWHM) for the same ^{60}Co γ peak. Later work centered about a 2.5%-efficient five-sided coaxial detector having a resolution of ≈2.2 keV and a peak-to-Compton ratio of 16.5 : 1. The most recent experiments were effected with a 10.4% efficient five-sided coaxial detector having a resolution of 2.1 keV and a peak-to-Compton ratio of 36 : 1. The remainder of the system consisted of linear amplifiers having near-Gaussian pulse shaping, pole-zero compensation, and baseline restoration, and 4096-channel analyzers of analog-to-digital converters interfaced to computers.

The energies of the γ rays were measured by counting the $^{53}Fe^{m+g}$ sources simultaneously with a number of well-known calibration sources. Using an oscilloscope computer code, a background correction was made for each peak by fitting higher order equations (usually cubic) to channels above and below each peak and then subtracting. Having determined the centroids of the standard peaks, a quadratic calibration equation was prepared for comparison with the $^{53}Fe^{m+g}$ centroids. Once the energies of the stronger $^{53}Fe^{m+g}$ γ rays were established, these were used as internal standards to verify the energies of weaker transitions present in the spectrum. Peak areas were converted to γ-ray intensities through curves previously determined in this laboratory for each detector. These curves were obtained using a set of standard γ-ray sources whose relative intensities had been measured carefully with a 7.6×7.6-cm NaI(Tl) detector. For more details concerning the methods of data collection and analysis, see, e.g., Ref. 20.

Having performed more than 30 singles experiments with this nucleus, including following the half-lives of numerous γ rays, we have succeeded in identifying at least 10 γ rays resulting from the

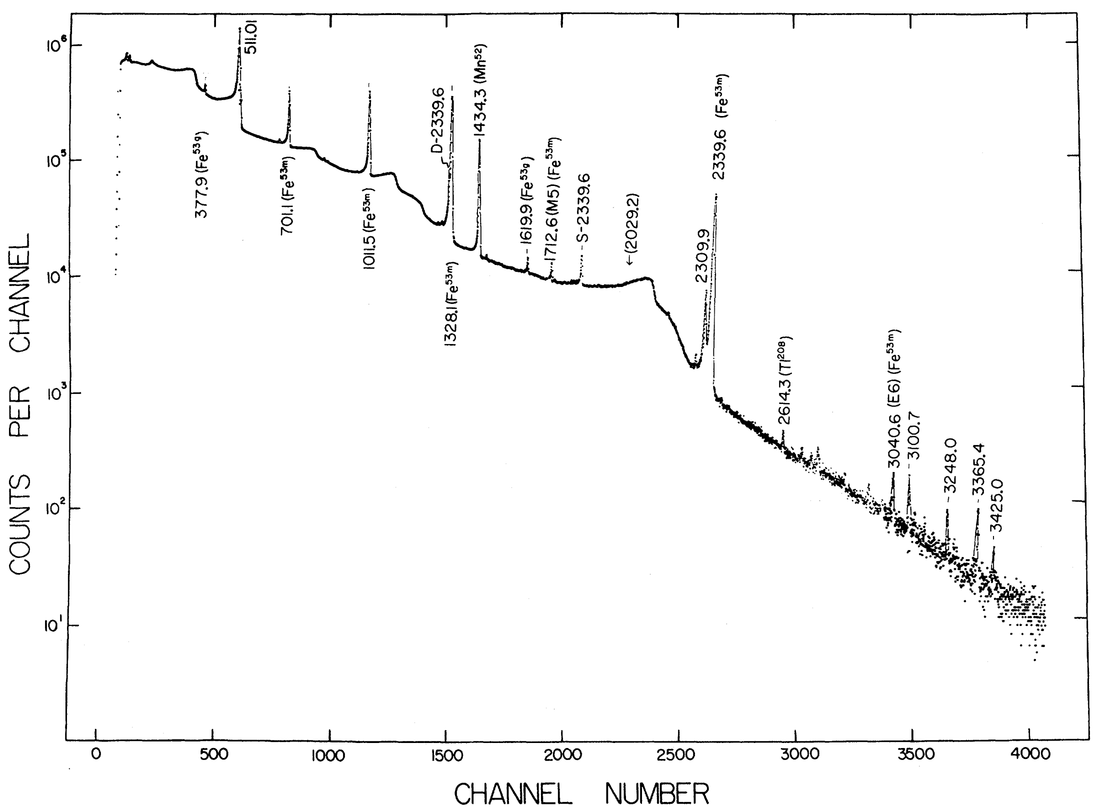

FIG. 2. Singles γ-ray spectrum of $^{53}Fe^{m+g}$ taken with a 3.6% efficient Ge(Li) detector under conditions to optimize the $^{53}Fe^{m}$ γ rays. This spectrum required 24 h to collect.

β^+/ϵ decay of $^{53}Fe^g$ and six from the isomeric decay of $^{53}Fe^m$. A singles spectrum that emphasizes the low-energy γ rays, taken with the 2.5% detector, is shown in Fig. 1. Some of the very weak transitions can be seen more clearly in Fig. 2, which shows a singles spectrum designed to locate the high-multipolarity γ transitions following the decay of $^{53}Fe^m$ and consequently emphasizes the higher-energy γ rays—more about this spectrum in Sec. III C. Many repeated bombardments, sometimes with chemical separations, were required to produce these spectra. (Figure 1, for example, represents some 17 h of counting time.) The $^{53}Fe^g$ and $^{53}Fe^m$ γ rays and their intensities are given in Tables I and II, respectively.

B. γ-ray coincidence spectra

1. *Anticoincidence spectra*

Even in a relatively simple decay scheme like $^{53}Fe^{m+g}$, it is important to determine which transitions are ground-state transitions, particularly if these could be primarily ϵ fed. In order to obtain such information, we performed a number of anticoincidence experiments using a 20-cm^3 Ge(Li) detector and 20.3×20.3-cm NaI(Tl) split annulus.[21] Briefly, this setup works as follows: The Ge(Li) detector is placed inside one end of the annulus tunnel and a 7.6×7.6-cm NaI(Tl) detector is inserted in the other end, with the source between them. The Ge(Li) detector is then operated in an anticoincidence mode (resolving time, $2\tau \approx 200$ nsec) with either (optically isolated) half of the annulus or the 7.6×7.6-cm detector. A 23-h accumulation taken in the above mode contained only the 377.9-keV γ ray. Thus, we see that it is most likely the only *strong* β^+/ϵ fed transition feeding the ground state of ^{53}Mn. The weaker γ rays, such as the 1619.9-keV transition, do not appear in the various coincidence spectra because of the poor statistics associated with these experiments. (The spectra described in this and the next three subsections can be found in Ref. 22.)

TABLE I. $^{53}Fe^g$ γ rays and intensities.

E_γ (keV)	Relative intensity
377.9 ± 0.1	≡100
(1288.0 ± 0.1) [a]	<0.20
1397.6 ± 0.8	0.02 ± 0.01
1619.9 ± 0.1	1.20 ± 0.20
2273.5 ± 0.3	0.90 ± 0.10
2307.7 ± 0.6	0.03 ± 0.01
2685.6 ± 0.4	0.19 ± 0.05
2748.8 ± 0.4	0.33 ± 0.08
2946.0 ± 0.4	0.12 ± 0.04
3248.8 ± 0.8	0.09 ± 0.05

[a] The 1288.0-keV level is fed very weakly by the β^+ decay of $^{53}Fe^g$. The inclusion of the 1288.0-keV γ ray here is based upon results obtained in experiments having high statistics.

2. *Any-coincidence spectra*

By performing a coincidence experiment in which any observed γ ray is used as a gate for any other γ ray seen within the resolving time ($2\tau \approx 100$ nsec), one may ascertain which transitions are in cascades. For our studies the most effective of these experiments again used the 20.3×20.3-cm NaI(Tl) split annulus. A 7-cm^3 Ge(Li) detector was placed inside one end of the annulus and operated in coincidence mode with either half of the annulus. An 18-h accumulation of $^{53}Fe^{m+g}$ taken in this configuration clearly showed that the 701.1-, 1011.5-, 1328.1-, and 2339.6-keV transitions are all in coincidence. Additional any-coincidence experiments, including those using only a 7.6×7.6-cm NaI(Tl) detector to gate a Ge(Li) detector, substantiated these results.

3. *Coincidences with the 377.9-keV γ ray*

Experiments were performed in an attempt to find γ rays which were in coincidence with the strong 377.9-keV transition in ^{53}Mn. The most effective experimental configuration used was a 7-cm^3 Ge(Li) detector placed in the 20.3×20.3-cm NaI(Tl) split annulus and operated in coincidence with either half of the annulus, both halves of which were gated on the 377.9-keV region. Such a gated experiment revealed none of the assigned $^{53}Fe^{m+g}$ γ rays. (Again, very weak γ rays such as the 2307.7- or the 2748.8-keV γ rays would not be expected to appear in these spectra.)

4. *511-keV-511-keV-γ coincidence (pair) spectra*

The two halves of the 20.3×20.3-cm NaI(Tl) split annulus were used in conjunction with a 20-cm^3 Ge(Li) detector to determine the β^+ feeding to levels in ^{53}Mn and to identify possible double-

TABLE II. $^{53}Fe^m$ γ rays and intensities.

E_γ (keV)	Relative intensity
701.1 ± 0.1	≡100
1011.5 ± 0.1	86 ± 9
1328.1 ± 0.1	87 ± 8
1712.6 ± 0.3	1.3 ± 0.1
2339.6 ± 0.1	13 ± 2
3040.6 ± 0.5	0.06 ± 0.01

escape peaks. Each half of the annulus was gated on the 511-keV $\gamma^{\pm}$ peak, and a triple coincidence (resolving time $2\tau \approx 100$ nsec) was required among these and the Ge(Li) detector. From the resulting spectra, only the 377.9-keV state in ^{53}Mn (other than the ground state) appears to be strongly β^{+} fed.

C. High multipolarity γ transitions following the decay of $^{53}Fe^{m}$

The discovery of the high-energy high-spin three-quasiparticle isomer in ^{53}Fe provided an excellent opportunity for the direct observation of very high multipolarity γ-ray transitions. The existence of $M5$, $E6$, and higher multipolarities has never been substantiated directly by experimental fact except for their presence as small admixtures occasionally being invoked to explain small discrepancies in experiments such as angular correlations.

Having confirmed Eskola's decay scheme[14,15] for $^{53}Fe^{m}$, we initiated a program to search for hitherto unobserved transitions of multipolarity $M5$ and $E6$. Source preparation was carried out as described above with bombardment time, beam energy, and all other parameters adjusted to optimize the production of the metastable state. γ rays were detected with a 3.6% efficient true-coaxial Ge(Li) detector having a resolution of 2.0 keV. The remainder of this system consisted of an amplifier having high-rate baseline restoration and a 50-MHz analog-to-digital converter interfaced to a Sigma-7 computer. Graded lead absorbers having a combined thickness of $\approx$3 cm were used between the source and the detector to attenuate the lower-energy γ rays. Even so, counting rates as high as possible without appreciable deterioration of resolution were maintained throughout the experiments, with an average count rate of about 6700 counts/sec. This combination of isomer optimization, detector efficiency and resolution, and high-count-rate electronics was deemed absolutely necessary in order to obtain the number of events necessary for direct observation of the weak $E5$ and $M5$ transitions.

Various spectra were taken at different times and with widely different geometries, and they produced consistent results. Figure 2 shows the

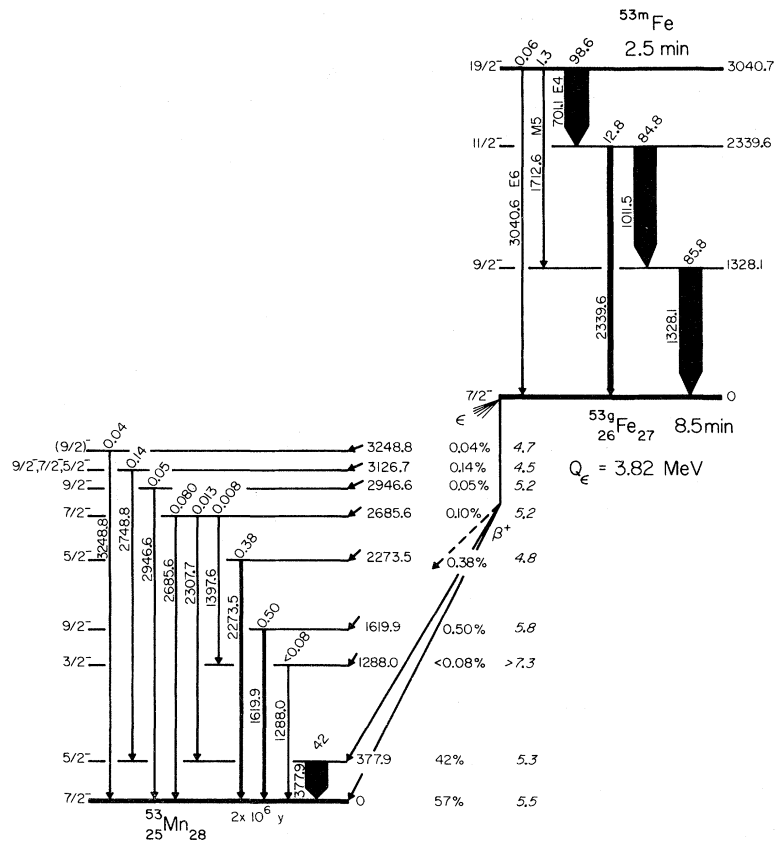

FIG. 3. Decay schemes of $^{53}Fe^{m}$ and $^{53}Fe^{g}$. Energies are given in keV and (total) transition intensities are given in percent of $^{53}Fe^{m}$ or $^{53}Fe^{g}$ decays. The logft's are given in italics to the right of the β intensities.

spectrum resulting from a 24-h accumulation of data obtained with the source on the axis of the detector and at a 10-cm distance. During this time a continuous cycle of bombarding and counting was maintained such that a fresh source was counted every 2 min. Definite peaks exist in this spectrum at the energies of 1712.6 and 3040.6 keV, where the $M5$ and $E6$ transitions are expected to occur. After careful energy and intensity analysis, these peaks were found to correspond to transitions having intensities of 1.3×10^{-2} and 6×10^{-4} relative to unity for the 701.1-keV transition. Experiments using the large 10.4%-efficient Ge(Li) detector showed that these peaks decay with the 2.5-min half-life of $^{53}Fe^{m}$ and are the only peaks in the spectrum (other than the four well-known intense $^{53}Fe^{m}$ peaks) that decay with this half-life.

Having shown that these peaks are present, one is obligated to demonstrate that they are indeed true peaks and not merely the resultant sum peaks of two or more known constituents. Such sum peaks are known to occur in large-volume detectors under high-count-rate conditions and can originate from two different physical conditions. First, if the source is sufficiently close to the detector so that the detector presents a large solid angle, summing of events in the same γ-ray cascade can occur. Second, if the source is strong, accidental summing of events from the same or different γ-ray cascades can occur. With our $^{53}Fe^{m}$ experiments one needs to worry about both effects in turn.

This summing problem was examined both in light of the data themselves and also from additional experiments designed to elucidate the summing phenomenon. Considering the $^{53}Fe^{m}$ data alone, we can formulate several interesting arguments. Examination of the established decay scheme (Fig. 3) reveals that two of the most intense transitions, at 701.1 and 1328.1 keV, are in a cascade connected by the 1011.5-keV transition, the third most intense. If indeed cascade-type summing were to occur to an appreciable extent during an experiment such as that recorded in Fig. 2, one would conclude that these two most intense transitions should give rise to a sum peak at 2029.2 keV. Examination of the spectrum, however, shows no evidence for a γ ray at this energy. This absence was reproducible from experiment to experiment, with widely varying detector sizes, count rates, and source-detector distances. One can estimate from this spectrum, for example, that the contributions from summing to the $M5$ and $E6$ peaks would be considerably less than 0.1% and 10%, respectively, and come almost entirely from chance coincidences. Also, although the 511.01-keV $\gamma^{\pm}$ peak was the most intense peak in the spectrum, no evidence was found for $\gamma^{\pm}$ summing to give a 1022-keV peak, or of their summing with any of the stronger γ rays in the spectrum. This indicates that chance-type summing was not a significant factor in these experiments except for a small possible contribution to the weak $E6$ peak. A third consideration is the peak width. In general, sum peaks or peaks containing significant summing components tend to be wider than their true counterparts. However, here one finds the peaks corresponding to the $M5$ and $E6$ transitions to be of normal width, providing further evidence for the fact that they are true peaks. Finally, the $E6$ and $M5$ transitions decay with the same half-life as the $E4$ isomeric transition, and one would expect to measure a different half-life if there were a substantial contribution from chance-coincidence summing.

To check the internal data, a series of experiments was performed in which ^{60}Co spectra were taken with various source-detector geometries at a constant count rate. The degree of summing to form a 2505.7-keV sum peak was observed as a function of geometry. Then, using the same count rates and geometries, an analogous set of $^{53}Fe^{m}$ spectra was taken. The resulting intensity variations of the $M5$ and $E6$ peaks as a function of geometry were compared with the variations of the ^{60}Co spectra. This method corroborated the fact that the 1712.6- and 3040.6-keV peaks were not sum peaks but do indeed reflect true transitions in the ^{53}Fe nucleus.

IV. β^{+} EXPERIMENTAL DATA

A number of techniques were used to obtain data about the β^{+} feedings from $^{53}Fe^{g}$, including β^{+} singles spectra taken with plastic detectors and a Si(Li) surface-barrier detector, also various γ-β^{+} coincidence spectra. Details of these experiments are given in Ref. 22, and the most important results are summarized as follows.

In Table III we list the end points and relative intensities of the three β^{+} groups we were able to resolve. (The γ-β^{+} coincidence spectra were re-

TABLE III. β^{+} relative intensities for $^{53}Fe^{g}$.

This work		Juliano *et al.* (Ref. 3)	
E_{β^+} (MeV)	Relative intensity (%)	E_{β^+} (MeV)	Relative intensity (%)
2.80 ± 0.10	57 ± 8	2.84 ± 0.10	50
2.40 ± 0.10	42 ± 8	2.38 ± 0.10	38
1.71 ± 0.35	≈1	1.57 ± 0.15	12

TABLE IV. Comparison of ^{53}Mn states below 3.82 MeV ($^{53}Fe^{g}$ Q_{ϵ}) seen via different selected experiments.

This work (β,γ) E (keV)	J^{π}	Juliano *et al.* (Ref. 3) (β,γ) E (keV)	J^{π}	Vuister (Ref. 4) (p,γ) E (MeV)	J^{π}	Maripuu (Ref. 5) (p,γ) E (keV)	J^{π}	Wiest *et al.* (Ref. 7) ($p,n\gamma$) E (keV)	J^{π}	Szöghy, Cujec, and Dayras (Ref. 8) ($\alpha,p\gamma$) E (MeV)	J^{π}	Tanaka *et al.* (Ref. 9) (p,n) E (keV)	Veje *et al.* (Ref. 10) (p,α) E (MeV)	J^{π}	O'Brien *et al.* (Ref. 11) (τ,d) E (MeV)	J^{π}
0	$\frac{7}{2}^-$	0	$\frac{7}{2}^-$	0	$\frac{7}{2}^-$	0	$\frac{7}{2}^-$	0	$\frac{7}{2}^-$	0	$\frac{7}{2}^-$	0	0	$\frac{7}{2}^-$	0	$\frac{7}{2}^-$
377.9	$\frac{5}{2}^-$	380	$(\frac{5}{2}^-)$	0.378	$\frac{5}{2}^{(-)}$	378	$\frac{5}{2}^-$	378	$\frac{5}{2}^-$	0.378	$\frac{5}{2}^-$	379 ±2	0.37	···	0.385	$\frac{5}{2}^-$
1288.0	$\frac{3}{2}^-$	1290	···	1.290	···	1290	$\frac{3}{2}^-$	1288.5	$\frac{3}{2}^-$	1.290	$\frac{3}{2}^-$	1290 ±3	1.28	···	1.296	$\frac{3}{2}^-$
···	···	···	···	···	···	···	···	1440	$\frac{11}{2}^-$	1.438	$\frac{11}{2}^-$	1440 ±3	1.43	···	···	···
1619.9	$\frac{9}{2}^-$	···	···	···	···	···	···	1619	$\frac{9}{2}^-$	1.617	$\frac{9}{2}^-$	1622 ±3	1.60	···	···	···
···	···	···	···	(1.94)	···	···	···	···	···	···	···	···	···	···	···	···
2273.5	$\frac{5}{2}^-$	···	···	2.281 [a]	···	2275	$\frac{5}{2}$	2772	$\frac{7}{2}, \frac{5}{2}$	2.271	$\frac{5}{2}^{-(+)}$	2277 ±3	2.26 [a]	···	···	···
···	···	···	···	···	···	···	···	···	···	···	···	···	···	···	2.370	$l_p=1$ [b]
···	···	···	···	2.406	···	2408	$\frac{3}{2}^-$	2405	$\frac{3}{2}$	2.404	$\frac{3}{2}^-$	2410 ±3	2.39 [a]	···	2.413	···
···	···	···	···	2.58 [a]	···	2573	···	2571	$(\frac{7}{2})$	···	···	2575 ±3	2.55	···	···	···
···	···	···	···	2.675 [a]	···	2672	$\frac{1}{2}^-$	2669 [a]	···	···	···	2672 ±3	2.67	···	2.678 [a]	···
2685.6	$\frac{7}{2}^-$	···	···	···	···	2689 [a]	$\frac{5}{2}$	2685	$\frac{7}{2}$	···	···	2690 ±3	···	···	···	···
···	···	···	···	2.70 [a]	···	2708	$\frac{1}{2}^+$	2705	···	···	···	2707 ±4	···	···	2.720 [a]	$\frac{1}{2}^+$
···	···	···	···	···	···	2839	···	···	···	···	···	···	···	···	···	···
···	···	···	···	2.86 [a]	···	2876	$\frac{3}{2}^-$	2875	$\frac{3}{2}$	···	···	? {2.873 ±4 2.880 ±4	2.86 [a]	···	2.882 [a]	$l_p=1$ [b]
···	···	···	···	2.91 [a]	···	2913	$\frac{3}{2}^-$	2911	···	···	···	2914 ±4	2.92	···	···	···
2946.6	$\frac{9}{2}^-$	···	···	···	···	···	···	2949	$\frac{9}{2}$	···	···	2947 ±4	···	···	···	···
···	···	···	···	(3.00) [a]	···	···	···	3004	$(\frac{3}{2}, \frac{5}{2})$	···	···	3008 ±5	2.98 [a]	···	{3.010 [a]	$\frac{3}{2}^-$
···	···	···	···	···	···	···	···	···	···	···	···	···	···	···	{3.061	$l_p=3$ [b]
···	···	···	···	···	···	3098	$\frac{3}{2}^-$	3095	···	···	···	3100 ±5	···	···	3.104 [a]	$l_p=1$ [b]
···	···	···	···	3.19 [a]	···	···	···	···	···	···	···	···	3.18 [a]	···	···	···
3126.7	$\frac{9}{2}^-, \frac{7}{2}^-, \frac{5}{2}^-$	···	···	···	···	···	···	3124	···	···	···	3127 ±5	···	···	···	···
···	···	···	···	···	···	3182	$\frac{3}{2}^-$	3180	···	···	···	3183 ±5	···	···	···	···
···	···	···	···	···	···	···	···	3199	$\frac{5}{2}-\frac{9}{2}$	···	···	3201 ±5	···	···	···	···
3248.8	$(\frac{9}{2})^-$	···	···	···	···	···	···	3248	$(\frac{9}{2})$	···	···	3249 ±5	···	···	···	···

TABLE IV *(Continued)*

This work (β,γ) E (keV)	J^π	Juliano *et al.* (Ref. 3) (β,γ) E (keV)	J^π	Vuister (Ref. 4) (p,γ) E (MeV)	J^π	Maripuu (Ref. 5) (p,γ) E (keV)	J^π	Wiest *et al.* (Ref. 7) $(p,n\gamma)$ E (keV)	J^π	Szöghy, Cujec, and Dayras (Ref. 8) $(\alpha,p\gamma)$ E (MeV)	J^π	Tanaka *et al.* (Ref. 9) (p,n) E (keV)	Veje *et al.* (Ref. 10) (p,α) E (MeV)	J^π	O'Brien *et al.* (Ref. 11) (τ,d) E (MeV)	J^π
...	...	...	...	...	...	3480	$\frac{1}{2}^-$	...	...	...	...	c	...	...	3.484	$l_p=1$ [b]
...	...	...	...	...	...	...	...	...	...	...	...	c	...	...	3.669	$l_p=3$ [b]

[a] There is poor cross calibration among some of the experiments; hence these states, although listed on the same line, may or may not be the same ones in fact.

[b] $l_p=1$ allows J^π values of $\frac{1}{2}^-$, $\frac{3}{2}^-$, or $\frac{5}{2}^-$; $l_p=3$ adds $\frac{7}{2}^-$ and $\frac{9}{2}^-$ possibilities.

[c] Reference 9 lists 11 other states below 3.82 MeV.

lied on heavily to obtain the β^+ energies.) This was done with a 1000-μ thick 200 mm^2 Si(Li) surface barrier detector at methanol-dry ice temperature ($\approx -77\,^\circ$C). Inasmuch as this detector (the best available at the time) is thin compared with the 6000 μm range of 2.8-MeV β^+ particles in Si, there is considerable uncertainty in the relative intensities. However, these uncertainties cannot be nearly large enough to reconcile them with the intensities of Juliano *et al.*,[3] as can be seen in Table III. In particular, the β^+ group(s) feeding states in ^{53}Mn higher than 377.9 keV cannot have an intensity much greater than $\approx 1\%$.

This is corroborated by the γ-ray intensities (cf. Table I). None of the γ rays with energies above 377.9 keV has an intensity anywhere approaching the 12% that Juliano *et al.* found for their third β^+ group; indeed, the sum of these higher-energy γ rays does not nearly reach 12%. Also, the results from γ-β^+ coincidence experiments are consistent with the low intensity. Using a 7.6×7.6-cm NaI(Tl) γ detector to gate the Si(Li) electron detector, a 2.4-MeV β^+ group was found to be in coincidence with the 377.9-keV γ, and no even moderately intense β^+ groups were found to be in coincidence with γ rays of higher energy.

V. PROPOSED DECAY SCHEMES

The data yielded by the β^+ and γ-ray experiments described above were fitted into consistent decay schemes for ^{53}Fe^g and ^{53}Fe^m. Both of these are presented in Fig. 3. The energies (except for Q_ϵ) are given in keV, and transition intensities are given in percent with respect to ^{53}Fe^g or ^{53}Fe^m disintegrations. Internal conversion coefficients are all small enough to be negligible, so photon intensities are used as total γ-transition intensities. Inasmuch as the β^+/ϵ ratios are not known experimentally, the logft values were calculated for the lowest four states assuming all β^+ decay and for the highest five states assuming all ϵ decay—this makes for simpler corrections if they are needed in the future.

A. States in ^{53}Mn populated by the decay of ^{53}Fe^g

1. ^{53}Mn ground state

A large portion ($\approx 50\%$) of the ^{53}Fe^g decay proceeds directly to the ground state in ^{53}Mn. This long-lived state ($t_{1/2} \approx 2\times10^6$ yr) has been shown experimentally to have $J^\pi = \frac{7}{2}^-$.[23] β^+ feeding to this state with an end-point energy of 2.8 MeV has been demonstrated by both β^+ singles and β^+-γ coincidence experiments. The β^+ group feeding this state has an allowed shape[3] and the logft value is 5.3. The calculated $\epsilon(K)/\beta^+$ ratio[24] for such a transition is only 0.013, and, indeed, for all practical purposes there is no ϵ decay to any of the lower-lying states in ^{53}Mn.

2. 377.9-keV state

The only intense γ ray in the $^{53}Fe^{g}$ spectrum was the one reported at 370 keV by Nussbaum, van Lieshout, and Wapstra[2] in 1953. (Previous investigations had characterized ^{53}Fe decay only as β^+ emission with an end point of ≈2.6 MeV.[25]) This γ ray, of course, deexcites the first excited state in ^{53}Mn, and from our energy for the γ ray we assign an energy of 377.0 ± 0.1 keV to this state. β^+-γ experiments both in this laboratory and elsewhere[3] have shown that this state is fed by a β^+ group having an end-point energy of 2.4 MeV. This group appears to have an allowed shape[3] and yields a logft value of 5.1. All the available data, both β^+ decay and reactions studies, are in agreement with the original $\frac{5}{2}^-$ assignment for the 377.9-keV state (cf. Table IV). This is consistent also with other odd-mass nuclei in the $f_{7/2}$ region.

3. 1288.0-keV state

This investigation furnished the first definite γ-ray evidence for ϵ/β^+ feeding to higher-lying levels in ^{53}Mn from the decay of $^{53}Fe^{g}$. Heretofore, the only evidence for these levels has been obtained through the various in-beam γ-ray and particle-transfer reactions (cf. Table IV). Indeed, we have drawn freely on some results of the more precise data in Table IV to aid us in our decay scheme construction.

The 1288.0-keV state appears to be populated only very weakly if at all by the decay of $^{53}Fe^{g}$. Only experiments with very high statistics such as those from the $E6$ search revealed this level. Earlier workers using other reactions together with scattering experiments have reported a level near 1290.[3,5] The β^+ spectra analyses indicate group(s) near 1.2–1.4 MeV which may feed this level. A more positive statement about this feeding cannot be easily obtained, since resolution of the third or fourth β group in a Fermi plot is at best a tedious and somewhat inaccurate procedure, particularly with our thin detector. Also, the extremely weak nature of this γ ray does not permit a reliable β^+-γ coincidence experiment to be performed. Calculations (cf. Sec. VI) indicate that the second excited state of ^{53}Mn should have $J^\pi = \frac{3}{2}^-$, which is also consistent with other odd-mass nuclides in this region. A number of in-beam measurements, including the precise $^{53}Cr(p, n\gamma)^{53}Mn$ experiments of Wiest *et al.*,[7] have verified this assignment. It would require that any direct β decay to it from $^{53}Fe^{g}$ would necessarily be second-forbidden, so our lower limit of 7.3 for the logft value is not particularly meaningful. Nevertheless, in view of some indication of excess 1288.0-keV γ intensity in a few high statistics spectra (cf. Fig. 2) and the fact that in other regions of the periodic chart there appear to be possible interference effects between forbidden and allowed β transitions,[26] one should keep an open mind about whether the feeding is real or is a result of experimental errors.

4. 1619.9-keV state

ϵ/β^+ population of this state is weak but the strongest to any higher-lying state in ^{53}Mn, and the logft value is 5.8. Its deexciting 1619.9-keV γ ray shows up well in every spectrum we took, and it definitely follows the $^{53}Fe^{g}$ half-life. This is undoubtedly the state that receives the weak β^+ feeding having an end point in the region of 1.2–1.4 MeV, as described in Sec. IV B 2. It has been assigned $J^\pi = \frac{9}{2}^-$ by a number of investigators[6-8] using in-beam γ-ray angular distribution techniques, and our results are consistent with this assignment.

5. Other states

Since 99% of the $^{53}Fe^{g}$ decay populates either the ground or first-excited state of ^{53}Mn, the task of determining higher-lying states by the present approach is quite difficult. Distinguishing possible transitions from contaminants, background, and statistical fluctuations makes assigning them somewhat uncertain. A number of γ rays seen in this investigation remain "unidentified" even after elimination of all known contaminants—all are quite weak, but they appear to follow half-lives more or less compatible with that of $^{53}Fe^{g}$. Of these, seven could be placed *a posteriori*, knowing the positions of ^{53}Mn states as determined by Wiest *et al.*[7] through their $^{53}Cr(p, n\gamma)^{53}Mn$ experiments—in all cases these are consistent with other experiments when definite information exists (cf. Table IV). These seven γ rays have energies of 1397.6, 2273.5, 2307.7, 2685.6, 2748.8, 2946.6, and 3248.8 keV, and they deexcite states at 2273.5, 2685.6, 2946.6, 3126.7, and 3248.8 keV, as shown in Fig. 3. The inferred logft values (based on ϵ decay only) have surprisingly low values,[27] indicating the β decay to be definitely allowed. This has allowed us to narrow down some of the assignments of Wiest *et al.*, and we find $J^\pi = \frac{5}{2}^-$; $\frac{7}{2}^-$; $\frac{9}{2}^-$; $\frac{9}{2}^-$, $\frac{7}{2}^-$, $\frac{5}{2}^-$; and $(\frac{9}{2})^-$ for the five states listed in ascending order. The γ-ray deexcitation patterns to lower states are consistent with these assignments, although this is not a stringent test.

B. States in ^{53}Fe populated by the decay of ^{53}Fe^m

1. ^{53}Fe ground state

This ground state has a well-established spin of $\frac{7}{2}^-$ and a half-life measured precisely at 8.51 ± 0.02 min.[28] It is fed directly by all three identified higher states, with the largest contribution (85.8%) coming from the first excited state. We shall see in Sec. VI that to a good approximation it consists of two $f_{7/2}$ proton holes coupled to $J=0$ plus a single $f_{7/2}$ neutron hole.

2. 3040.7-keV metastable state

During excitation function studies, the concurrent appearance of γ rays having a half-life of 2.5 min with those of the known ^{53}Fe^g γ rays led to the belief that they comprised a metastable state in ^{53}Fe. Decay curve studies by Eskola[15] showed the parent-daughter relationship between the 2.5-min activity and the 8.5-min ^{53}Fe^g. Comparison of the excitation energy and half-life with single-particle estimates[29] indicated that the spins of the metastable and ground states differ by at least five units, indicating that the spin of the metastable state must be at least $\frac{17}{2}$. And, if the metastable state were interpreted as a three-particle state, its spin could well be $\frac{19}{2}$.[15] As discussed in Sec. IIIC, our finding of the weak $E6$ and $M5$ γ-ray branches from this state, together with the qualitative agreement of their (and the $E4$) transition probabilities (cf. Sec. VI) with predicted values, leads us to a conclusive $J^\pi = \frac{19}{2}^-$ assignment for this state.

It should be mentioned that careful consideration was made before eliminating the 1712.6- and 3040.6-keV transitions as occurring in ^{53}Mn following the β^+ decay of ^{53}Fe^m. If $\frac{19}{2}^-$ ^{53}Fe^m were to populate a 3040.6-keV state in ^{53}Mn, the $\log ft$ would be reasonable (≈ 5.7). However, if the 1712.6-keV transition were to deexcite this same state the $\log ft$ would be quite unreasonable (≈ 4); a 1328.1-keV state would also be necessary, and such a state has not been found in any scattering experiments. (It would be the third excited state and should certainly have been seen in at least some of these experiments.) An unreasonable $\log ft$ would also result from the 1712.6-keV γ ray's feeding the 1438-keV state from a 3151-keV state. And unreasonable $\log ft$'s would result from the 3040.6-keV γ ray's feeding any of the ^{53}Mn excited states from the 1288.5-keV state on up. A semigood energy fit would have the 3040.6-keV γ ray feeding the 1619.9-keV state and the 1712.6-keV γ ray feeding the 2946.6-keV state (from a state at 4660.5 vs 4659.2 keV), but the γ-ray intensities rule this out. In fact γ-ray intensity balances, particularly those involving the 1712.6-keV γ ray, rule out the possibility of the two γ rays belonging to ^{53}Mn. Thus we are quite sure that they are indeed $E6$ and $M5$ transitions in ^{53}Fe itself.

3. 2339.6-keV state

This state was placed on the basis of γ-ray sums and verified by coincidence relations.[15] Its $J^\pi = \frac{11}{2}^-$ was assigned on comparing the 701.1-keV γ transition probability with single-particle estimates,[29] which indicated this transition to be $E4$. Excitation-function experiments using the ^{50}Cr$(\alpha, n\gamma)^{53}$Fe reaction by Sawa and Bergström[30] have verified the $\frac{11}{2}^-$ assignment. Our results are consistent with this, and shell-model calculations (cf. Sec. VI) are consistent with it.

4. 1328.1-keV state

Until the present investigation, assignment of the first excited state of ^{53}Fe could have been made at either 1320.1 or 1011.5 keV. (However, see note added in proof.) Shell-model calculations hinted that the first excited state lay at the higher energy. Differences in the predicted $M1$ vs $E2$ branching ratio from the 2339.6-keV state were not significant or trustworthy enough to make the choice. However, the 1712.6-keV $M5$ transition

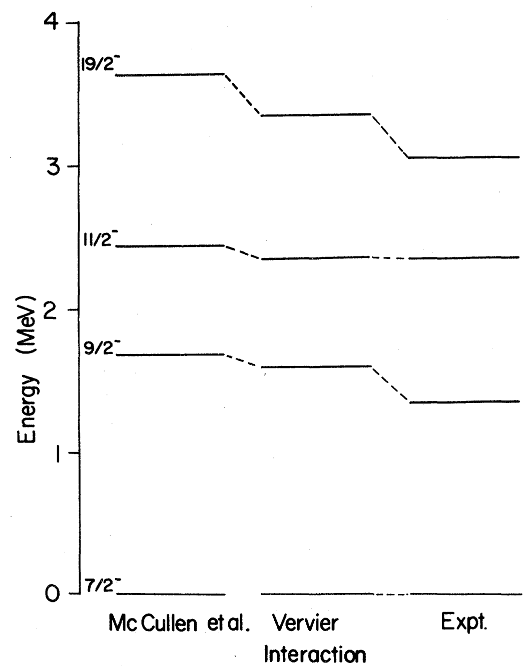

FIG. 4. Schematic comparison of ^{53}Fe experimental levels with those calculated by McCullen, Bayman, and Zamick (Ref. 34) and by us using the Vervier interaction number 3.

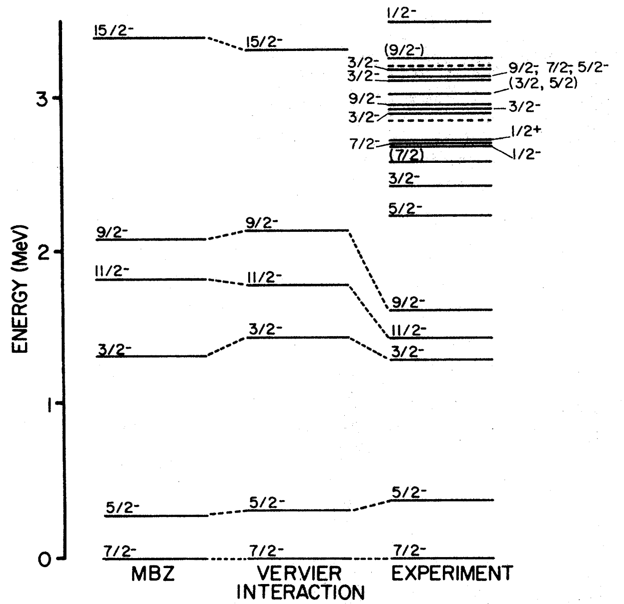

FIG. 5. Schematic comparison of ^{53}Mn experimental levels with those calculated by McCullen, Bayman, and Zamick (Ref. 34) and by us using the Vervier interaction number 3.

from $^{53}Fe^{m}$ definitely places the first excited state at 1328.1 keV. The $J^{\pi}=\frac{9}{2}^{-}$ assignment for this state is consistent with all γ branching ratios, shell-model calculations, and experiments by Sawa and Bergström.[30]

VI. SHELL-MODEL ANALYSIS OF EXPERIMENTAL RESULTS

The simplest theory for the states in ^{53}Fe and ^{53}Mn studied in the present experiments assumes that their structure can be explained in terms of a pure $f_{7/2}$ configuration; three $f_{7/2}$ holes in the present instance. Many calculations[31-35] have been made in this framework and all yield results which qualitatively agree with the experimental data on the states in question, and with one another.

In Figs. 4 and 5 we show the results obtained for ^{53}Fe and ^{53}Mn with an interaction of Vervier (interaction No. 3 of Ref. 31). It is interesting to note that the $f_{7/2}{}^{-3}$ model with empirical Hamiltonians quite consistently predicts the occurrence of the ^{53}Fe isomerism, which arises from the depression of the $\frac{19}{2}^{-}$ level below the $\frac{15}{2}^{-}$ level. We have used the wave functions obtained for ^{53}Fe with Vervier's interaction in calculations of the electromagnetic decay strengths of the $\frac{19}{2}^{-}$ level. The calculations were made with the codes of French, Halbert, McGrory, and Wong.[36] The wave functions we ob-

TABLE V. ^{53}Fe calculated wave functions using vervier interaction (3) (Ref. 31).

J^{π}	Wave function [a]
$\frac{7}{2}^{-}$	$0.764\Pi_0+0.608\Pi_2$
	$+0.187\Pi_4-0.104\Pi_6$
$\frac{9}{2}^{-}$	$0.921\Pi_2+0.387\Pi_4$
	$-0.032\Pi_6$
$\frac{11}{2}^{-}$	$0.772\Pi_2+0.606\Pi_4$
	$-0.191\Pi_6$
$\frac{19}{2}^{-}$	$1.00\Pi_6$
$\frac{1}{2}^{-}$	$1.00\Pi_4$
$\frac{3}{2}^{-}$	$0.886\Pi_2+0.463\Pi_4$
$\frac{5}{2}^{-}$	$-0.521\Pi_2-0.245\Pi_4$
	$+0.817\Pi_6$
$\frac{13}{2}^{-}$	$0.943\Pi_4-0.332\Pi_6$
$\frac{15}{2}^{-}$	$0.879\Pi_4-0.477\Pi_6$
$\frac{17}{2}^{-}$	$1.00\Pi_6$

[a] $\Pi_0=(\pi f_{7/2})^{-2}_{J=0}(\nu f_{7/2})^{-1}$; $\Pi_2=(\pi f_{7/2})^{-2}_{J=2}(\nu f_{7/2})^{-1}$; $\Pi_4=(\pi f_{7/2})^{-2}_{J=4}(\nu f_{7/2})^{-1}$; $\Pi_6=(\pi f_{7/2})^{-2}_{J=6}(\nu f_{7/2})^{-1}$.

TABLE VI. Comparison of experimental results for partial half-lives with Moszkowski single-particle values (SPV) and with $f_{7/2}{}^{-3}$ shell-model predictions (SMP).

E (keV)	Multipolarity	Photon intensity	Partial half-life Expt [a]	SPV	SMP	Retardation (Expt/SPV)	(Expt/SMP)
701.1	$E4$ [b]	98.6	1.57×10^{2}	4.0×10^{1}	3.0×10^{1}	3.9	5.2
1712.6	$M5$ [b]	1.3	1.17×10^{4}	2.7×10^{3}	9.3×10^{1}	4.2	12.6
3040.6	$E6$ [b]	0.06	2.6×10^{5}	1.1×10^{5}	2.7×10^{4}	2.3	9.7

[a] The 701.1-keV transition was corrected for conversion using a value of $\alpha_K=0.003$, which we obtained by a linear extrapolation from the tables of R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968). The conversion coefficients for the other transitions were small enough to be negligible.

[b] The next most reasonable multipolarities, $M3$, $E4$, and $M5$, would have SPV half-lives of 4.8×10^{-4}, 1.25×10^{-2}, and 5.0 sec, respectively. This clearly eliminates a possible $\frac{17}{2}^{-}$ assignment for the 3040.7-keV state.

tained are listed in Table V.

The experimental results for the decay of the $\frac{19}{2}^-$ isomeric level in ^{53}Fe are compared to single-particle estimates and to the predictions of the $f_{7/2}{}^{-3}$ shell model in Table VI. (It should be noted that there are some numerical errors in Table I of Ref. 17, and that table should be replaced by the present Table VI.) The calculations assume a unit charge for protons and zero charge for neutrons. It is seen that the observed transition rates are all significantly *retarded* with respect to the calculations. This situation is anomalous when viewed in the light of the customary *enhancement* of $E2$ transition strengths over the single-particle and zero-effective charge shell-model estimates. It is also difficult to discern mechanisms which would significantly alter the essence of the shell-model results.

It is quite plausible that the states with lower spin have wave functions which contain significantly more mixing between various fp shell orbits than does the $\frac{19}{2}^-$ state. Nonetheless, the amount of mixing necessary to bring about the needed retardation is much beyond what is normally thought acceptable.[37] Another avenue of explanation is that the effective charges for the high multipolarity transitions (that is, the renormalizations which result from basis space truncations) may be small to negative, compared to the large positive values empirically deduced for $E2$ transitions. There is little to no experimental evidence to support such a hypothesis, and theoretical estimates, while suggestive that the effective charge should be lower for $E6$ than for $E2$ transitions, also cannot account for the retarded rates observed. In view of the straightforward experimental situation and the supposedly simple theoretical picture, the failure to obtain a more accurate understanding of these phenomena constitutes an intriguing puzzle.

Note added in proof: Nelson *et al.*[38] have studied low-lying states in ^{53}Fe via the ^{54}Fe$(p,d)^{53}$Fe and ^{50}Cr$(\alpha,n\gamma)^{53}$Fe reactions, and they find a $\frac{3}{2}^-$ state at 741 keV. Their findings are consistent with and confirm our discussion in Sec. V B. It is interesting to note, however, that they find many more low-lying states than predicted by any of the shell-model calculations.

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