Disintegration of Iron-52 and Iron-53†

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The disintegration of Fe^{52}(8.2 hours) and Fe^{53}(8.9 min) has been investigated with the help of scintillation and coincidence counting equipment. Fe^{52} decays 56.5% by positron emission and 43.5% by electron capture. The end-point energy of the positron group is 0.804 ± 0.01 Mev. This is followed by a gamma ray of energy 165 kev leading to Mn^{52m}(21 min). The chain $Fe^{52}\rightarrow Mn^{52}\rightarrow Cr^{52}$ has been studied. In addition to the well-known states of Mn^{52}—the ground state, with character 6+ and half-life of 5.7 days, and the first excited state (Mn^{52m}), with character 2+, half-life of 21 min, and energy of 390 kev—these experiments show a third excited state at 555 kev having a configuration 0+ and a half-life of $(1.2\pm0.2)\times10^{-8}$ sec. The disintegration of Fe^{53} is accompanied by the emission of a gamma ray of energy 380 kev and positron groups of end-point energies 2.84 ± 0.10, 2.38 ± 0.10 Mev, and an indication of third group at 1.57 ± 0.15 Mev.

INTRODUCTION

IRON-52, an 8-hour nuclide decaying by both positron emission and electron capture, was first reported by Miller, Thompson, and Cunningham.[1] Its positron spectrum in equilibrium with the daughter Mn^{52m} was determined precisely with a magnetic spectrometer by Arbman and Svartholm[2] and they reported positron energies of 0.804 ± 0.010 Mev and 2.631 ± 0.015 Mev for Fe^{52} and Mn^{52m}, respectively. The Fermi-Kurie plots were those of allowed beta transitions. Iron-52, being an even-even nuclide, presumably has a ground-state assignment[3] of 0+; and if so, there should be in excited state in Mn^{52} with a spin of either 0 or 1 and positive parity which is populated by the allowed 0.804-Mev positron group of Fe^{52}. The ground state of Mn^{52} has a spin of 6 and positive parity[4,5] and that of Mn^{52m} is probably 2+ since the half-life of Mn^{52m} together with its reported 390-kev gamma ray[6] is consistent with that of an $E4$ transition.[7] Therefore it seemed obvious that there should be a transition in Mn^{52} which is populated by the positrons of Fe^{52} but not yet detected. This was also pointed out by Way *et al.*[8] in 1955. Recently, Barr,[9] in his cross-section measurements on the spallation reaction of copper with 6-Bev protons, reported that a 163-kev gamma ray, having an 8-hour half-life, was present in the iron fraction. It was the hope of finding out whether or not this gamma ray comes from an excited state of Mn^{52}, populated by the positron decay of Fe^{52}, thus clarifying the decay chain $Fe^{52}\rightarrow Mn^{52}\rightarrow Cr^{52}$, that prompted this investigation.

Iron-53 was also produced in this experiment together with Fe^{52}. Since the decay of Fe^{53} to Mn^{53} is still definitely not known, a short bombardment was made to produce the 9-minute isotope of iron. Two previous investigations have been made on Fe^{53}, namely: that by Nelson and Pool[10] in which they reported no gamma rays but only positrons with an end-point energy of 2.6 Mev, and the other by Nussbaum[11] and Nussbaum, van Lieshout, and Wapstra[12] in which a gamma ray at 0.370 Mev was reported. They also presented some inconclusive evidence for gamma rays at 0.92 and 1.3 Mev. Hence to settle these contradictions it was decided to reinvestigate the disintegration of Fe^{53}.

PROCEDURE

Analytical grade chromium (Cr^{50}, 4%; Cr^{52}, 84%; Cr^{53}, 10%; and Cr^{54}, 2%), was plated on a silver probe and bombarded with alpha particles by the Indiana University cyclotron, for 30 minutes in the case of Fe^{53} and for 8 hours in the case of Fe^{52}. The sources were dissolved in hot concentrated HCl and the iron oxidized to its ferric state with hot *aqua regia*. Iron, manganese, indium, and gallium carriers in the form of chlorides were added prior to the chemical separations. The iron was extracted by diethyl ether from a 6N HCl solution and precipitated with NaOH to remove any trace of gallium extracted into the ether layer. The ferric hydroxide precipitate was dissolved by a dilute HCl solution and evaporated on a thin Mylar film for beta and gamma-ray studies.

The positron spectrum was obtained with an anthracene crystal, $1\frac{1}{2}$ in. in diameter and 1 in. thick, used in conjunction with a DuMont 6292 photomultiplier tube

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[1] Miller, Thompson, and Cunningham, Phys. Rev. **74**, 347 (1948).
[2] E. Arbman and N. Svartholm, Arkiv Fysik **10**, 1 (1956).
[3] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[4] Abraham, Jeffries, Kedzie, and Leifson, Bull. Am. Phys. Soc. Ser. II, **2**, 382 (1957).
[5] Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **110**, 787 (1958).
[6] R. K. Osborne and M. Deutsch, Phys. Rev. **71**, 467(A) (1947).
[7] M. Goldhaber and A. W. Sunyar, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. 16, Part II.
[8] *Nuclear Level Schemes*, $A=40-A=92$, compiled by Way, King, McGinnis, and van Lieshout, Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955), p. 42.
[9] D. W. Barr, University of California Radiation Laboratory Report, UCRL-3793, May, 1957 (unpublished).
[10] M. E. Nelson and M. L. Pool, Phys. Rev. **77**, 682 (1950).
[11] R. H. Nussbaum, thesis, Amsterdam (unpublished).
[12] Nussbaum, van Lieshout, and Wapstra, Phys. Rev. **92**, 207 (1953).

whose output was amplified in the conventional manner and analyzed by a 100-channel pulse-height analyzer. The positron groups were resolved into their components by a Fermi-Kurie plot and corrected for finite resolution using the formulas of Palmer and Laslett.[13]

The electromagnetic transitions were determined with a 1 in.×1 in. NaI(Tl) crystal attached to a DuMont 6292 photomultiplier tube in conjunction with a 100-channel pulse-height analyzer. The gamma-ray energies and relative intensities were calibrated with the transitions of Cs^{137}, Bi^{207}, Mn^{54}, Na^{22}, and Hg^{203}.

Beta-gamma coincidences were measured with the help of a $1\frac{1}{2}$ in.×$1\frac{1}{2}$ in. NaI(Tl) crystal mounted on a DuMont 6292 tube as the gamma detector and a 1 in. high by $1\frac{1}{2}$ in. diameter anthracene crystal mounted on a DuMont 6292 tube as the positron counter. For the shorter half-life Fe^{53}, a 20-channel pulse-height analyzer, gated by the 380-kev gamma-ray pulses selected by a single-channel pulse-height analyzer, was used to display the positron spectrum in coincidence with the 380-kev gamma ray. With the longer-lived Fe^{52}, a conventional fast-slow coincidence circuit was used to determine the positrons in coincidence with the gamma rays. In all the gamma-positron coincidence runs, the gamma-ray pulses were used as gate pulses and the corresponding coincident-positron distributions were measured.

EXPERIMENTAL RESULTS

The purity of the sources was checked by measuring the rate of decay of the samples. In Fig. 1 is shown the half-life measurements of Fe^{52} and Fe^{53}. From the results of the several runs the half-life of Fe^{52} was found to be 8.2±0.1 hours and that of Fe^{53}, 8.9±0.1 minutes. Mn^{52m}, the daughter of Fe^{52}, was separated from Fe^{52}

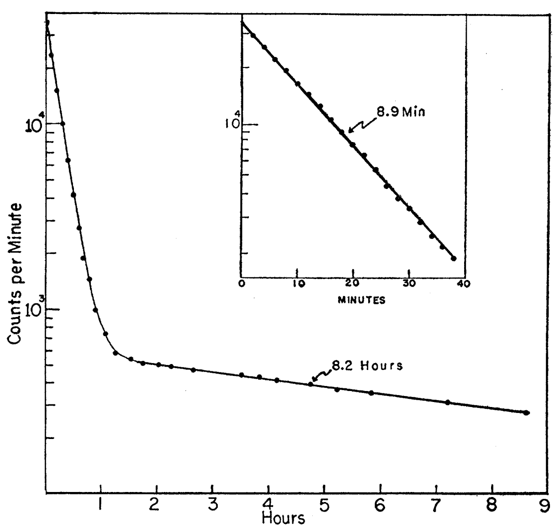

FIG. 1. Decay curve of Fe^{52}(8.2 hr) and Fe^{53}(8.9 min).

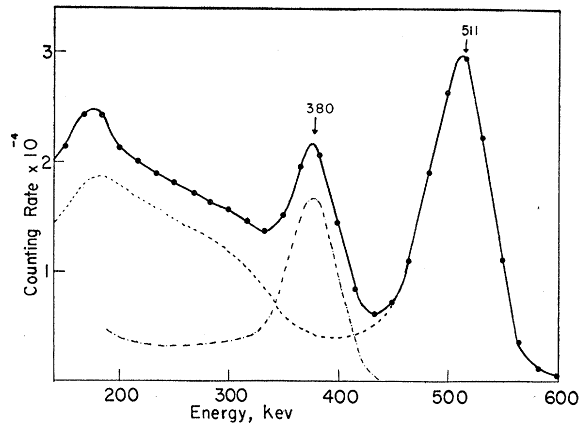

FIG. 2. Gamma-ray spectrum of Fe^{53}.

and its half-life also measured. It was 21.1±0.2 minutes. After all the Fe^{52}, Fe^{53}, and Mn^{52m} had decayed, the residual activity, which was quite weak, decayed with a half-life of approximately 6 days, in close agreement with the reported 5.7-day Mn^{52}.[14]

EXPERIMENTS ON Fe^{53}

The gamma-ray spectrum of Fe^{53} is shown in Fig. 2. This was taken one hour after the bombardment at which time Fe^{53} comprised 90% and Fe^{52} only 10% of the total activity. Two gamma rays were seen having energies of 380 kev and 511 kev (annihilation radiation). After correcting for the Fe^{52} contribution to the annihilation-radiation peak the relative intensity of the 380-kev line to the total positron spectrum (511-kev annihilation radiation) was 32%. The gamma ray at 380 kev decayed with a half-life of 9 minutes, while that at 511 kev decayed with a composite half-life, so that two hours later only the 511 kev, now due to Fe^{52} alone, was left. Attempts were made to detect the 1.3- and 0.92-Mev transitions reported by Nussbaum[11,12] but they were not observed in this investigation. The positron groups of Fe^{53}, however, seem to indicate the presence of an excited level at 1.3 Mev which would mean that the electromagnetic transitions, if present, were too weak to be detected.

In less than an hour after the bombardment, the positron spectrum of Fe^{53} was measured [Figs. 3(a) and (b)]. Three groups, all having allowed shapes within the accuracy of an anthracene crystal spectrometer, were resolved and their corresponding energies, intensities, and calculated logft values are given in Table I. Since the beta counter was calibrated only with Cs^{137} (624 kev) and Bi^{207} (976 and 481) kev conversion electrons, the error in the energy calibration especially at about 2 Mev and higher would permit us to say that the difference in energy between the two high-energy positron groups corresponds to the observed 380-kev

[13] J. P. Palmer and L. J. Laslett, U. S. Atomic Energy Commission Bulletin, ISC-174, 1950 (unpublished).

[14] Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 585 (1958).

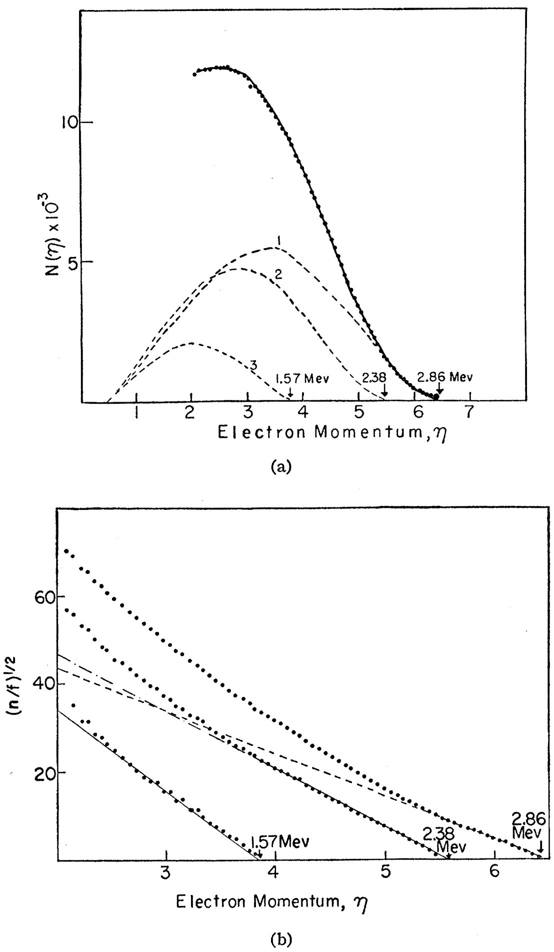

FIG. 3. (a) Positron spectrum of Fe^{53}. (b) Fermi-Kurie plot of the positron spectrum of Fe^{53}.

electromagnetic transition. Taking into consideration also the percentage distribution of the particles, it would seem reasonable to say that the 2.4-Mev group feeds the 380-kev level. In order to say conclusively which particle group populates the 380-kev gamma ray, a beta-gamma coincidence experiment was performed. The positron spectrum between 1.4 and 2.8 Mev was displayed on a 20-channel pulse-height analyzer both with and without gating with the 380-kev gamma-ray pulses. The Fermi plot of the positrons in coincidence with the 380-kev line had an end point of 2.4 Mev which was 0.4 Mev less than the most energetic group of the ungated positron spectrum. If we consider the energy available for decay of Fe^{53} to Mn^{53} (3.7 Mev[14]), the

TABLE I. Positron groups of iron-53.

Group No.	Energy, Mev	Relative abundance, %	logft
I	2.84±0.10	50	5.32
II	2.38±0.10	38	5.12
III	1.57±0.15	12	4.90

2.8 Mev-positron group populating the ground state of Mn^{53} is within the energy available for decay.

EXPERIMENTS ON Fe^{52}

The gamma-ray spectrum of Fe^{52} taken after the Fe^{53} had died out (15 hours after the bombardment) is shown in Fig. 4. It has a strong 165-kev peak, a 511-kev annihilation radiation peak, and a weak 1430-kev gamma-ray peak. The 165-kev line decayed with an 8-hour half-life and those at 511 and 1430 kev mainly with an 8-hour period so that a few days later only the 511-kev and the 1430-kev lines remained together with the 730- and 940-kev gamma rays of Mn^{52} which appeared. Mn^{52m} was separated from the Fe^{52} parent and its gamma spectrum showed only the 0.511- and 1.43-Mev lines. This 1.43-Mev line is the transition from the 1.43-Mev excited state of Cr^{52} to its ground state which is populated by positrons of Mn^{52m}. The 390-kev gamma ray reported for the Mn^{52m} was not seen in this investigation because of its being highly converted and weakly populated (0.05%).[14]

Immediately after separating Fe^{52} from the other activities and allowing for the complete decay of Fe^{53}, the positron spectrum was obtained and resolved into two groups: namely, 2.60 Mev and 0.82 Mev with the relative intensities 1:1.1. At this moment the Mn^{52m} was not yet in equilibrium with Fe^{52} and hence there were more Fe^{52} disintegrations per unit time than there were of Mn^{52m}. Fifteen hours later, when the Fe^{52} was in equilibrium with its daughter Mn^{52m}, the positron spectrum was redetermined and the same energy groups were obtained, but this time the relative intensity of the groups was 1:0.55, for the 2.60 Mev and 0.82 Mev, respectively [Fig. 5(a)]. The two positron groups were resolved in both cases into their Fermi components and exhibited allowed shapes. Arbman and Svartholm[2] reported 1:0.565 for this ratio from an Fe^{52}-Mn^{52m} equilibrium mixture with a 180° magnetic spectrometer. From the change in particle distributions before and after equilibrium, it is inferred that the 0.82-Mev group belongs to the parent Fe^{52}. As a further check, the Mn^{52m} daughter was separated from the Fe^{52} parent and its positron spectrum measured. Here only the 2.6-Mev

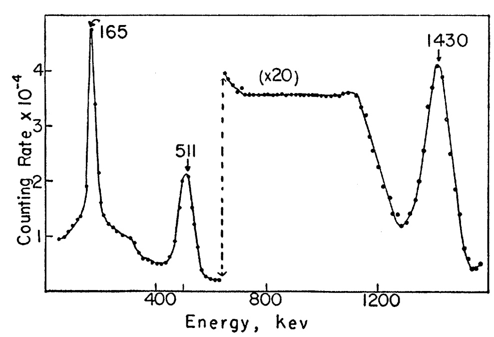

FIG. 4. Gamma-ray spectrum of Fe^{52}.

group was found thereby associating the 2.6-Mev positrons with the Mn^{52m}. A few days later when all the Fe^{52} and Mn^{52m} had decayed, the residual activity showed a positron end point of approximately 0.6 Mev and gamma rays of 0.73, 0.94, and 1.43 Mev, characteristic of Mn^{52}.

A more rigid test of the position of the 165-kev transition in the decay scheme was made with the help of beta-gamma coincidence experiments. By using a fast-slow coincidence circuit with a resolving time (2τ) of 1.0×10^{-7} second, the positron spectrum in coincidence with the 165-kev line was determined. The result is shown in Fig. 5(b). A Fermi plot of this spectrum gives an end point of about 800 kev and no other coincidences were found at energies higher than 800 kev. In Fig. 5(b), it is seen that the particle distribution continuously increased as the particle energy decreased. The increase at energies lower than the maximum of the 800-kev positron group was due to the annihilation radiation—165-kev line coincidence contribution to the actual 165-kev—gamma-ray—positron coincidences. Upon placing enough absorber to stop all positrons, corrections could be made for the contribution of the gamma-gamma coincidences. The results show that the 800-kev positron group of Fe^{52} feeds the 165-kev gamma ray of Mn^{52}. Since this transition is an allowed one, the spin of the level depopulated by the 165-kev gamma ray should be either 0 or 1, with positive parity. Hence, the 165-kev gamma ray cannot populate the 6+ ground state of Mn^{52}, for that would be a much delayed transition. The only plausible position for this transition is for it to feed the supposed 2+ state of Mn^{52m}. If this is so, a further study on the multipolarity of the 165-kev transition by lifetime measurements would be helpful, especially since it was noted that, by using Rose's[15] tables of K, L_{I}, and L_{II} conversion coefficients for this transition, the K/L ratio of the conversion line intensities could not differentiate between an $M1$ and an $E2$ transition. When the positron spectrum in coincidence with the 1.43-Mev line was determined, it was found that only the 2.6-Mev positron fed this gamma ray [Fig. 5(c)].

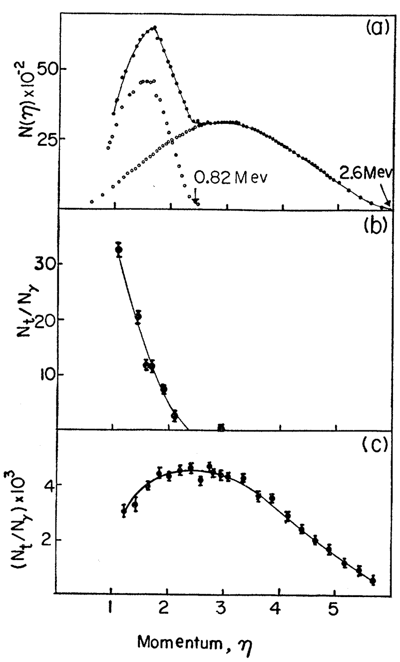

FIG. 5. (a) Positron spectrum of an equilibrium mixture of Fe^{52} and Mn^{52m}; (b) in coincidence with the 165-kev gamma ray; (c) in coincidence with the 1430-kev gamma ray.

The lifetime of the state giving rise to the 165-kev transition was measured using the delayed-coincidence technique. Two different approaches were made: First, one channel was set on the 165-kev gamma line and the other channel on the positron spectrum in the energy range of 400 to 500 kev; and second, by setting one channel on the 165-kev gamma line and the other channel on the 511-kev annihilation-radiation line. This procedure was followed in order to check for instrumental effects, principally any effect due to having used an anthracene crystal in one channel and a NaI(Tl) crystal in the other for the first measurement. It was evident from the results that no differences were seen.

For the first measurement (beta-gamma delayed coincidences) a fixed delay of 0.20 microsecond was inserted in the 165-kev gamma channel and a continuously variable delay (0 to 1.00 microsecond) was inserted in the beta channel. The coincidence counting rate as a function of the delay in the beta channel was measured as the delay was changed from zero to 0.55 microsecond. As the delay was increased from the direction of zero delay, the coincidence counting rate approached a maximum, with a slope measured on a semilogarithmic plot corresponding to a half-life of 25 millimicroseconds [Fig. 6(a)]. After the variable delay passed 0.40 microsecond, in the direction of increasing delay, the coincidence counting rate began to fall off with a slope corresponding to a half-life of 14 millimicroseconds, which was interpreted as the slope to be expected from a prompt-coincidence measurement. The resolving time (2τ) of the fast-slow coincidence circuit, in this case, was seen to be 0.40 microsecond in agreement with a value obtained through the measurement of accidental coincidences with two independent sources. The ratio of true to accidental coincidences at the maximum coincidence counting rate was about 211. The maximum statistical error (one standard deviation) was 5%, due mainly to the number of counts observed. The difference between the two slopes corresponded to a half-life of 11 millimicroseconds for the 165-kev gamma line.

The second method was to determine the lifetime of the state by using the 165-kev gamma ray and the 511-kev annihilation radiation. As in the previous run, a 0.20-microsecond fixed delay was inserted in the 165-kev gamma channel and a continuously variable delay (0 to 1.00 microsecond) was placed in the 511-kev channel.

[15] M. E. Rose, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), Chap. 14.

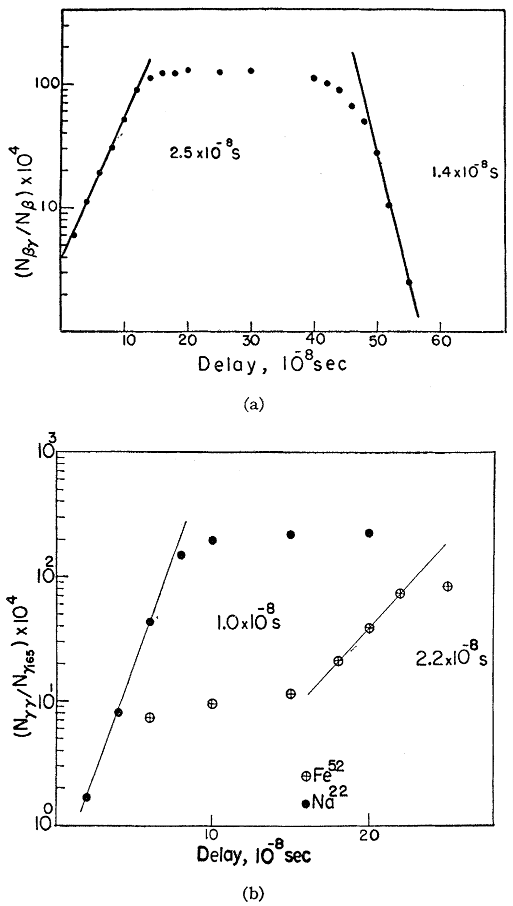

FIG. 6. Half-life measurements on the 555-kev excited state of Mn^{52} (a) from beta-gamma coincidences; (b) from gamma-gamma coincidences.

The coincidence counting rate as a function of the delay in the 511-kev channel was measured, this time as the delay was changed from zero to 0.25 microsecond, covering only the initial rise. The slope of this curve corresponded to a half-life of 22 millimicroseconds [Fig. 6(b)]. This was compared with the prompt-coincidence slope, using annihilation-radiation coincidences, corresponding to a half-life of 10 millimicroseconds. The prompt-coincidence curve, which was symmetric about a delay of 0.27 microsecond, was obtained with the two $1\frac{1}{2}$ in.$\times 1\frac{1}{2}$ in. NaI(Tl) crystals at 180° relative position while the 511-kev—165-kev coincidence curve was obtained with the two crystals at 95° relative position, to preclude the measurement of annihilation-radiation prompt coincidences. The errors were comparable in magnitude to those in the beta-gamma coincidence measurements. The ratio of true to accidental coincidences at the maximum counting rate was about 100 for the Fe^{52} and about 1500 for the prompt coincidences. The difference between the two slopes corresponded to a half-life of 12 millimicroseconds for the 165-kev line.

Based on the two different approaches to the determination of the half-life of the state giving rise to the 165-kev line, a final value of 12 ± 2 millimicroseconds was adopted. This is a very conservative figure and the actual results can be better than the errors expressed in the given value. The quoted error was a combination of that due to the number of coincidences which was observed and the spread in slopes which could be fitted to the experimental points.

DECAY SCHEMES

The proposed decay scheme for Fe^{52} is given in Fig. 7. Iron-52 decays 43.5% by electron capture and 56.5% by positron emission to the 555-kev excited state of Mn^{52}. This value was arrived at from the assumption that the 2.6-Mev positron group populates the 1.43-Mev level of Cr^{52} with a very negligible electron capture contribution and therefore the total decay to the 555-kev level by electron capture and positron emission should equal the intensity of the 2.6-Mev positron group at equilibrium. The ratio of the intensities of the two positron groups obtained in this experiment at equilibrium agrees remarkebly well with Arbman and Svartholm's[2] data, which are believed to be very re-

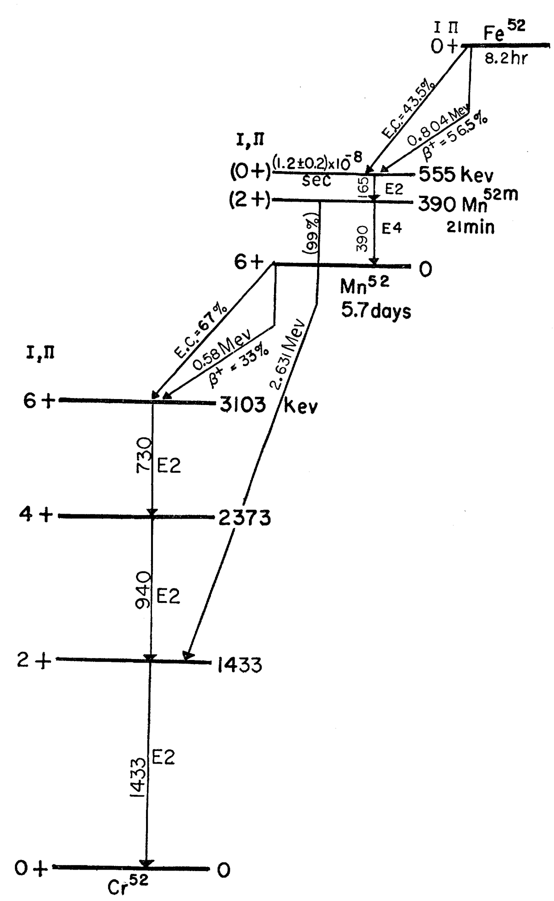

FIG. 7. Decay scheme of Fe^{52}.

liable. Zweifel's[16] theory predicts 1.1:1.0 for the positron to electron capture ratio population of the 555-kev level for an allowed transition while the experimental result was 1.3 to 1.0. The assumption therefore that the 2.6-Mev positron feeds mostly the 1.43-Mev level of Cr^{52} is reliable because the 2.6-Mev positron group is an allowed transition and from Zweifel's prediction the positron to electron-capture ratio for this energy and nuclide is 100 to 1. The 555-kev level was assigned a 0+ configuration based on the allowed decay classification of the 804-kev positron transition, the $E2$ multipolarity of the 165-kev gamma ray, and on the assumption that the 390-kev Mn^{52m} level is a 2+ state. The 165-kev electromagnetic transition was assigned an $E2$ multipolarity based solely on its half-life of $(1.2\pm0.2)\times10^{-8}$ second. Using Weisskopf's[7] single-particle (proton) transition probability formula for this energy and mass number, an $E2$ assignment should have a half-life of 3×10^{-7} second and an $M1$, 8×10^{-10} second. Hence, it can be said that an $E2$ assignment to a half-life of 1.2×10^{-8} second would imply the acceptance of an enhanced $E2$ electromagnetic transition. A more valid comparison was made using the decay of Co^{56} to Fe^{56} which has an 845-kev level of character (2+) which decays to the ground state (0+). This transition is known to be pure $E2$ and has a half-life of 6×10^{-12} second, determined from Coulomb excitation[17] of Fe^{56}. Calculating $\log_{10}\{\tau_\gamma \exp[A^{\frac{4}{3}}][E_\gamma(\text{Mev})]^5\}$ for this transition gives a value of -9.26 compared to -9.55 for the 165-kev gamma ray of Mn^{52} from the decay of Fe^{52}. This is a remarkable agreement although it is somewhat faster than the single-particle model predictions. Wilkinson,[18] however, in his studies of the lifetimes of light nuclides found that $E2$ transitions are enhanced by a factor of five over that predicted by the Weisskopf model and usually more than this near closed shells. Also, Sunyar[19] observed unusually fast $E2$ transitions among the rare earths which was attributed to some rotational motion of the nucleus. In other respects the proposed disintegration of $Fe^{52}\rightarrow Mn^{52}\rightarrow Cr^{52}$ shown in Fig. 7 agrees with the accepted decay scheme.[14]

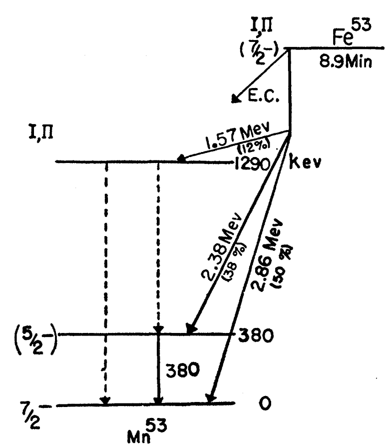

FIG. 8. Decay scheme of Fe^{53}.

Our results for Fe^{53} are given in Fig. 8. The nuclear shell model predicts that the ground state of Fe^{53} has the character $\frac{7}{2}-$. Dobrowolski, Jones, and Jeffries[20] measured the spin of $Mn^{53}(2\times10^6$ yr) by a paramagnetic resonance method and reported it to be $\frac{7}{2}$, in agreement with the shell model prediction. Hence it would be reasonable to assume that the shell model holds quite well in this region and thus assign a character $\frac{7}{2}-$ to the ground state of Fe^{53} and $\frac{7}{2}-$ to the ground state of Mn^{53}. The allowed shape and the $\log ft$ value of the positron transition of highest energy in Fe^{53} to the ground state of Mn^{53} is consistent with these assignments. In addition, the first excited state of Mn^{53} at 380 kev probably has a character $\frac{5}{2}-$ in keeping with other odd nuclei in this region ($f_{7/2}$ shell). Thus Ca^{43} has a first excited state of spin $\frac{5}{2}$ at 373 kev and V^{51} a similar state at 320 kev. Zeldes,[21] in his theoretical studies on the systematics of the energy levels in this region based on the shell model, reports that the excited states with the same spins have similar energies and that a plot of these levels as a function of their neutron number would show a linear relationship. Talmi,[22] in a different approach, comes to the same conclusion. Since no sudden jumps in energy are expected, a spin of $\frac{5}{2}$ and odd parity is compatible for the level at 380 kev. The allowed nature of the second positron group in Fe^{53} is consistent with this interpretation.

The present experiments lead to contradictory assignments for the spin and parity of the second excited state at 1.27 Mev. Theoretically, a $\frac{3}{2}-$ configuration would be expected for that state based on an analogy with the other nuclides in this part of the table of isotopes. Such an assignment would require that the positron group populating this state be second forbidden with a $\log ft$ of about 13, and a low relative abundance. Such a situation would explain the fact that no gamma rays emanating from the 1.27-Mev state were seen. The analysis of the positron distribution, using the scintillation method, showed a group having an end-point energy of 1.57 Mev and a relative abundance of 12%. It is to be remembered that this group was obtained after two subtractions and could be in error. Nevertheless, the positron distribution from Fe^{52}, obtained by a similar procedure, gave end-point energies and relative abundances in excellent agreement with the values obtained by Arbman and Svartholm[2] with the help of a magnetic

[16] P. F. Zweifel, in *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 300.
[17] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
[18] D. H. Wilkinson, in *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 175.
[19] A. W. Sunyar, Phys. Rev. **98**, 653 (1955).
[20] Dobrowolski, Jones, and Jeffries, Phys. Rev. **104**, 1378 (1956).
[21] N. Zeldes, Nuclear Phys. **7**, 27 (1958).
[22] I. Talmi, in *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 36.

spectrometer. In view of these contradictions the question of the population of the level at 1.27 Mev must be considered unsettled from the point of view of the present experiments.

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7.65-Mev State of C^{12}†*

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The angular distribution for the inelastic scattering of 42-Mev alpha-particles by C^{12}, with excitation of the 7.65-Mev state, has been measured. The experimental distribution shows maxima and minima consistent with 0^+ or 2^+ spin-parity assignment for the 7.65-Mev state, on an Austern, Butler, McManus type of direct interaction theory. A search was made for coincidences between the inelastically scattered alpha particles and recoil carbon nuclei in an attempt to determine the probability that the 7.65-Mev state decays by transitions to the ground state of C^{12}. It was found that there is less than one chance in ten that this probability exceeds 0.1%. This low probability is not inconsistent with current theories of helium burning in stars and provides additional support for the usual 0^+ assignment for the 7.65-Mev state.

I. INTRODUCTION

THE 7.65-Mev state of C^{12} has received attention beyond that given to many low-lying states of light nuclei due to its presumed role in the helium burning process in the buildup of elements and the production of energy in red giant stars. Reviews of the theory have recently been given by Salpeter[1] and Burbidge, Burbidge, Fowler, and Hoyle.[2] Cook, Fowler, Lauritsen, and Lauritsen[3] have confirmed that the state has an energy and a breakup mode into alpha particles consistent with its participation in helium burning. They have also summarized experimental evidence indicating that the state has zero spin and positive parity. While there is a strong preference for the 0^+ assignment, the evidence is not fully conclusive, especially in view of the uncertainty concerning the occurrence of electron pairs from this state.[4–6]

One purpose of the present experiment was to investigate the spin-parity assignment for this state by determining the angular distribution of inelastically scattered alpha particles, and comparing to predictions of simple theories[7,8] which have had some success in explaining angular distributions in inelastic scattering of alpha particles with excitation of states of known spin in light nuclei.[9] Measurements on the angular distribution of alpha particles scattered with excitation of the 7.65-Mev state of C^{12} have been made previously[10–13] without conclusive results. In particular Watters,[11] using 31.5-Mev alpha particles, finds an angular distribution consistent with a 0^+ assignment on the Austern, Butler, McManus[7] type of direct interaction theory, while Vaughn,[12] using 48-Mev alpha particles, finds a distribution inconsistent with such an assignment.

If, as assumed in helium-burning theories, the 7.65-Mev state of C^{12} can be formed from alpha particles it must, by the reversibility of nuclear reactions, be capable of breakup into alpha-particles and for this not to be a trivial process it must also decay, at least to some extent, to the ground state of C^{12}. The energetically possible decay modes of C^{12*} (7.65-Mev) may be summarized as follows:

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* A more complete account of this work appears in S. F. Eccles, Ph.D. thesis, University of Washington, 1958 (unpublished). Part of these results have been reported in S. F. Eccles and D. Bodansky, Bull. Am. Phys. Soc. Ser. II, 3, 188 (1958).
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