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Thermal Neutron Capture Gamma Rays in Iron*

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The gamma rays of Fe^{57} emitted following thermal neutron capture in Fe^{56} have been investigated by the measurement of coincidences between a three-crystal pair spectrometer and a single NaI(Tl) crystal. These data have been combined with information about the levels of Fe^{57} derived from the decay of Co^{57}, which has been re-examined here, the decay of Mn^{57}, and nuclear reaction data in order to determine the properties of several of the low-lying levels in Fe^{57}. The spins, parities, and decay characteristics of the first four excited states in Fe^{57} now appear to be established as well as the main features of the decay of the levels at 1.266, 1.630, and 1.728 Mev.

INTRODUCTION

THE experiment reported here represents a continuation of a program of investigations of gamma-ray cascades following thermal neutron capture. The experimental arrangement is similar to that used previously.[1] Briefly summarized, this technique consists of placing a target in an external neutron beam and measuring coincidences between two gamma-ray detectors placed close to the target. One detector is a single NaI(Tl) crystal usually, but not always, 3×3 in., and the other a three-crystal pair spectrometer, also composed of NaI(Tl) crystals.

Several improvements have been made in the experimental arrangement since the last report. They include:

(a) A two-dimensional 2048 (32×64) channel pulse-height analyzer[2] which records the pulse heights of both coincident gamma rays. This allows the accumulation in a single run of coincident spectra for a range of gamma-ray energies in each detector.

(b) A transistorized slow-fast coincidence circuit with a minimum resolving time of 2×10^{-8} sec.[3] In the present experiment, the resolving time was 5×10^{-8} sec.

(c) A new collimator for the neutron beam giving a minimum of neutrons hitting the materials which surround the target and having a favorable ratio of neutrons to gamma rays.

(d) A new shield for the counters, reducing the background both from neutrons scattered in the target and from external gamma rays and neutrons.

(e) Redesign of the photomultiplier stabilizing system.

These changes resulted in higher coincidence counting rates with a lower fraction of accidental counts, better energy resolution of the counters, and a higher over-all stability.

PREVIOUS WORK

More than 100 energy levels in Fe^{57} have been established from studies of the inelastic scattering of protons[4] in iron and confirmed in studies of the $Fe^{56}(d,p)Fe^{57}$ reaction.[5] With the exception of the first two excited states of Fe^{57}, whose energies have been measured with high precision in the decay of Co^{57},[6] the results of this work give the most precise values for the level energies, and are therefore adopted here.

High resolution studies of the capture gamma rays of iron have been made by Kinsey and Bartholomew[7] and by Ad'yasevich, Groshev, and Demidov.[8,9] Recent measurements by Vervier and Bartholomew[10] of the circular polarization of the 7.639-Mev gamma ray have established that this line is actually a doublet with 0.49 ± 0.19 of the intensity representing a ground-state transition and the remainder a transition to the 14 kev first-excited state. The same workers have determined the spin of the 0.366-Mev level to be $\frac{3}{2}$ by measuring angular correlations through this level.

The properties of the ground state, first-excited state at 0.014 Mev and second-excited state at 0.136 Mev have long been well established.[11]

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The 0.136- and the 0.366-Mev levels have been excited and their decay properties established in Coulomb excitation studies.[12,13]

The gamma-ray spectrum following the decay of Mn^{57} indicates decays to the 0.136-, 0.366-, and 0.707-Mev levels.[14] The spectrum following Co^{57} decay has been reported[15] to contain a 0.708-Mev gamma ray as well as the gamma rays emitted from the 0.136-Mev level. The total disintegration energy of Co^{57} has been reported[16] to be 0.57 Mev from a measurement of the inner bremsstrahlung end point. The reported 0.708-Mev gamma ray following Co^{57} decay is, of course, inconsistent with this determination of the total disintegration energy. A study[17] of the $Fe^{57}(p,n)Co^{57}$ reaction leads to the value of 0.89 ± 0.03 Mev for the Co^{57} total disintegration energy which is in disagreement with the inner bremsstrahlung determination but is consistent with the Co^{57} decay gamma-ray spectrum.

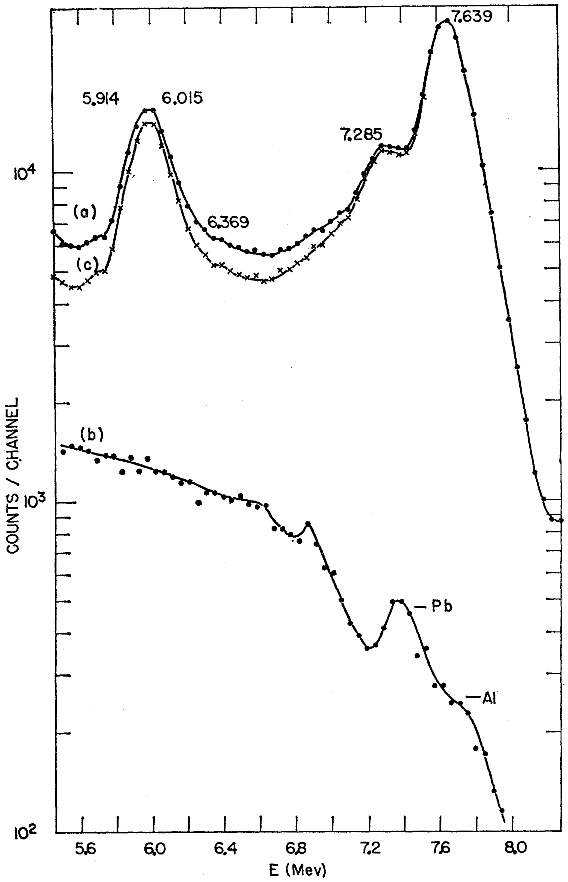

FIG. 1. (a) Pair spectrometer spectrum of the high energy capture gamma rays of iron. (b) Pair spectrometer spectrum with the iron replaced by a graphite target. (c) The spectrum shown in (a) with the background in (b) subtracted.

Recently,[18] a level at 0.82 Mev has been reported as being populated by the $Fe^{56}(d,p)Fe^{57}$ reaction. This level has not been reported in any of the other studies involving Fe^{57}.

RESULTS

High-Energy Gamma Rays

All results were obtained with the use of a disk-shaped target of magnet iron weighing 11.2 g. As a check on the purity of this sample high and low-energy singles spectra were also obtained with the use of a 1.2-g target of high-purity iron. The spectra of these two samples were identical.

A pair spectrometer spectrum of the capture gamma rays of iron in the region from 5.5 to 8 Mev is shown in Fig. 1(a). The features of this spectrum are in complete accord with the previous results of Kinsey and Bartholomew[7] and Ad'yasevich, Groshev, and Demidov.[8,9] The two highest energy peaks correspond to the 7.639- and 7.285-Mev gamma rays, and the broad peak at ~6 Mev to the 6.015- and 5.914-Mev gamma rays of Fe^{57}. A small peak corresponding to the 6.369-Mev gamma ray of Fe^{57} may also be seen.

The weak gamma rays in the spectrum at 6.6 and 6.8 Mev are believed to arise from the capture of scattered neutrons in the apparatus. This is borne out by the background spectrum, shown in Fig. 1(b), which was taken with a sample of graphite substituted for the iron. In addition to a continuous background, peaks appear at 6.6, 6.8, and 7.4 Mev. The 7.4-Mev peak is assumed to arise from the strong (~100%) 7.38-Mev gamma ray[19] of lead. The origin of the 6.6- and 6.8-Mev peaks has not been established. Neutron capture in the iodine of the NaI crystals should give rise to gamma rays with energies of 6.45 and 6.71 Mev.[20] Other known capture gamma rays with energies of[9] 6.6 and 6.8 Mev have been ruled out by the nonappearance of accompanying gamma rays with other energies.

A spectrum with the background obtained in the manner described subtracted from the original iron spectrum is presented in Fig. 1(c). The peaks in this spectrum are seen to have an asymmetric shape, with a considerable tail on the low-energy side. The low-energy tail arises from two instrumental effects. The first of these, present in all three-crystal spectrometers, is the escape of electrons and bremsstrahlung from the

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center crystal. The second, a consequence of the compact geometry required in the present experiment, is a loss of energy by the primary gamma rays by small-angle Compton scattering before reaching the detector.

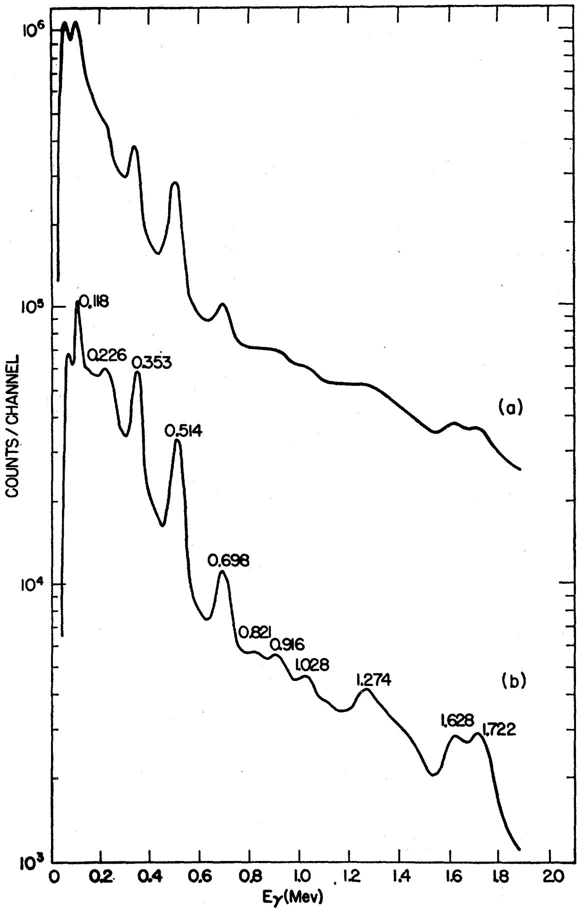

FIG. 2. (a) Low-energy capture gamma rays of iron detected by 3×3-in. NaI crystal. (b) Low-energy capture gamma rays of iron detected by a 3×3-in. NaI crystal coincident with high-energy gamma rays detected by the middle crystal of the pair spectrometer.

Low-Energy Gamma Rays

The low-energy capture gamma ray spectrum of iron, in the energy range 0.08 to 1.85 Mev, taken with a single 3×3 in. NaI crystal, is shown in Fig. 2(a). The spectrum contained considerable background, most of which was eliminated by requiring a coincidence with a gamma ray with energy ≥ 1 Mev, detected by the center crystal of the pair spectrometer. While such a spectrum is not quantitative in that it may not represent the true intensity distribution of the gamma rays, it nevertheless is useful in the identification of weak gamma rays and the measurement of their energies. A coincident spectrum of this type is shown in Fig. 2(b). The measured energies of the principal peaks are, as indicated, 0.118, 0.226, 0.353, 0.514, 0.698, 1.274, 1.628, and 1.722 Mev. Because of the compact counting geometry, a large back-scatter peak exists in the vicinity of the 0.226-Mev peak, making the energy of this peak somewhat uncertain. There may also be a slight shift in the measured energy of the 0.353-Mev peak owing to the Compton edge of the 0.514-Mev peak underneath it (at 0.325 Mev).

The principal component of the 0.514-Mev peak is 0.511-Mev annihilation radiation. However, this peak has a half breadth about 25% greater than the expected value. As will be shown later, this is due to a second component at 0.53 Mev.

The strong peak at 0.698 Mev probably corresponds to a transition from the 0.707-Mev level to the first-excited state at 0.014 Mev. In the existing level scheme, however, a 0.718-Mev transition between the 1.728- and 1.010-Mev levels is also possible. Both transitions may be present.

Several peaks are evident in the region from 0.8 to 1.6 Mev. As will be seen later, these correspond to a number of unresolved gamma rays.

The peaks at 1.628 and 1.722 Mev correspond to transitions from the levels at 1.630 and 1.728 Mev to the ground state or first-excited state. The combined uncertainties of the present results and of the positions of these levels[4,5] do not permit conclusions to be drawn as to whether these transitions proceed to the ground state or first-excited state.

Gamma Rays of Co^{57}

The gamma-ray spectrum of a Co^{57} source more than one year old was examined with the aid of a 3×3 in. NaI detector. A gamma ray with a measured energy of 0.696 ± 0.004 Mev was present with an intensity of $0.13 \pm 0.02\%$ per disintegration of Co^{57}. This presumably represents a transition from the 0.707-Mev level to one or both numbers of the ground-state—0.014-Mev doublet of levels. Previously, an energy and intensity of 0.708 Mev and 0.2% had been reported for this gamma ray.[15]

The only other gamma rays observed in addition to those already well established in the decay of Co^{57} were the 0.84- and 0.81-Mev gamma rays of Co^{56} and Co^{58}, respectively. The combined intensity of these was a factor of 10 smaller than that of the 0.696-Mev gamma ray.

An upper limit of 0.013% per decay of Co^{57} is set on the intensity of any $\sim$0.35-Mev gamma rays. These could arise either from an electron capture transition of Co^{57} to the 0.366-Mev level of Fe^{57} or from a 0.341-Mev transition from the 0.707-Mev level to this level. In the latter case there would be two $\sim$0.35-Mev gamma rays per transition. As a result, the probability of this mode of decay of the 0.707-Mev level is less than 5% of that of the 0.696-Mev transition. The intensity of a 0.571-Mev transition from the 0.707-Mev level to the 0.136-Mev level is estimated to be less than a tenth that of the 0.696-Mev transition.

The upper limit of $<1.3\cdot10^{-4}$ per Co^{57} decay for the feeding of the 0.366-Mev state leads to the lower limit $\log ft > 10$ for the β transition to this state.

COINCIDENCE RESULTS

The results of the measurement of coincidences between the high-energy capture gamma rays, detected by the three-crystal pair spectrometer and the low-energy gamma rays, detected by a single crystal are as follows.

7.639 Mev

Only the expected number of accidental counts were observed in coincidence with this unresolved doublet of gamma rays known to proceed to the ground state and 0.014-Mev first-excited state. No attempt was made in the present experiment to observe the 0.014-Mev gamma ray.

7.285 Mev

The low-energy spectrum coincidence with the 7.285-Mev gamma ray, which populates the 0.366-Mev level, is shown in Fig. 3. The peaks at 0.22 and 0.35 Mev correspond to transitions from the 0.366-Mev level to the 0.136- and 0.014-Mev levels, respectively. The relative intensities of the two gamma rays are 18±3 and 82±3%. These may be compared with relative intensities of 7 and 93% reported for the same two gamma rays from Coulomb excitation.[12]

The small peak at 0.511 Mev represents accidental coincidences with annihilation radiation.

We have previously reported[21] that the state at $\sim$0.365 Mev fed by capture gamma rays decays primarily to the first-excited state. It thus appears that the state excited through neutron capture gamma rays is indeed the same as that excited by Coulomb excitation.

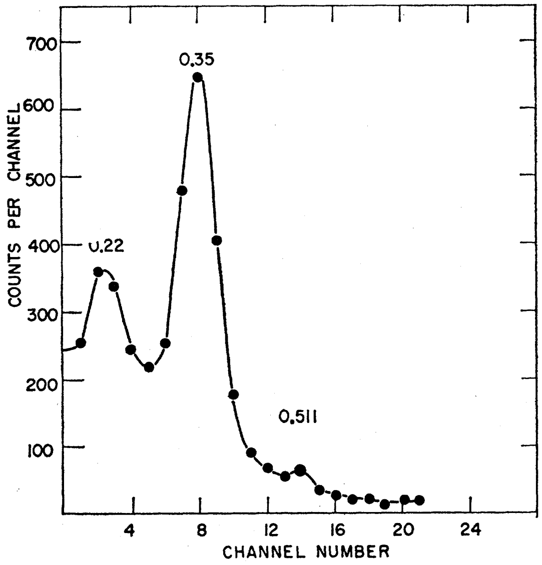

FIG. 3. Low-energy spectrum coincident with the 7.285-Mev gamma ray.

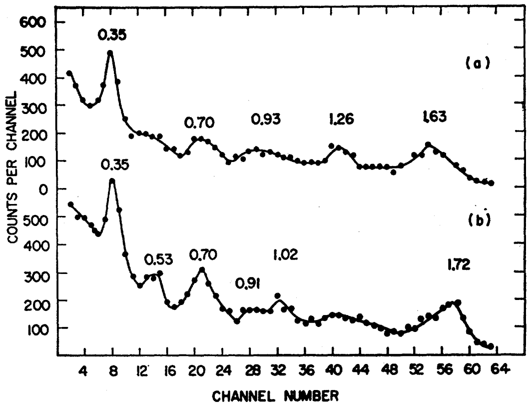

FIG. 4. (a) Low-energy spectrum coincident chiefly with the 6.015-Mev gamma ray. (b) Low-energy spectrum coincident chiefly with the 5.914-Mev gamma ray.

6.369 Mev

Gamma rays with energies of approximately 0.35, 0.93, and 1.27 Mev were observed in coincidence with the 6.369-Mev gamma ray which populates the 1.266-Mev level. These may be placed in the existing level scheme as a transition to the ground state or first-excited state and as a cascade through the 0.366 level. Weaker gamma rays were also seen at 0.54 and 0.70 Mev, representing a possible cascade through the 0.707-Mev level. The two leading modes of de-excitation have comparable intensities.

6.015 Mev

The spectra shown in Fig. 4(a) and (b) are coincident with portions of the incompletely resolved peak in the pair spectrum corresponding to the 6.015- and 5.914-Mev gamma rays. They are from a run of approximately 100 hr duration. In this run settings were chosen so that five channels in the pair spectrum covered the 5.914–6.015 Mev peak. Part (a) of Fig. 4 is the sum of the spectra coincident with the uppermost two of these five channels, and part (b) the sum of the spectra coincident with the lowest two channels. The middle channel has been omitted. Part (a) thus represents mainly gamma rays coincident with the 6.015 Mev transition to the level at 1.630 Mev, and part (b) gamma rays coincident with the 5.914-Mev transition to the level at 1.728 Mev, with some overlapping.

In part (a) of Fig. 4, gamma rays are present with energies of 0.35, 0.70, 0.93, 1.26, and 1.63 Mev. Evidently the 1.63-Mev gamma ray corresponds to a transition to the ground state or first-excited state. It appears to account for somewhat more than half of the total

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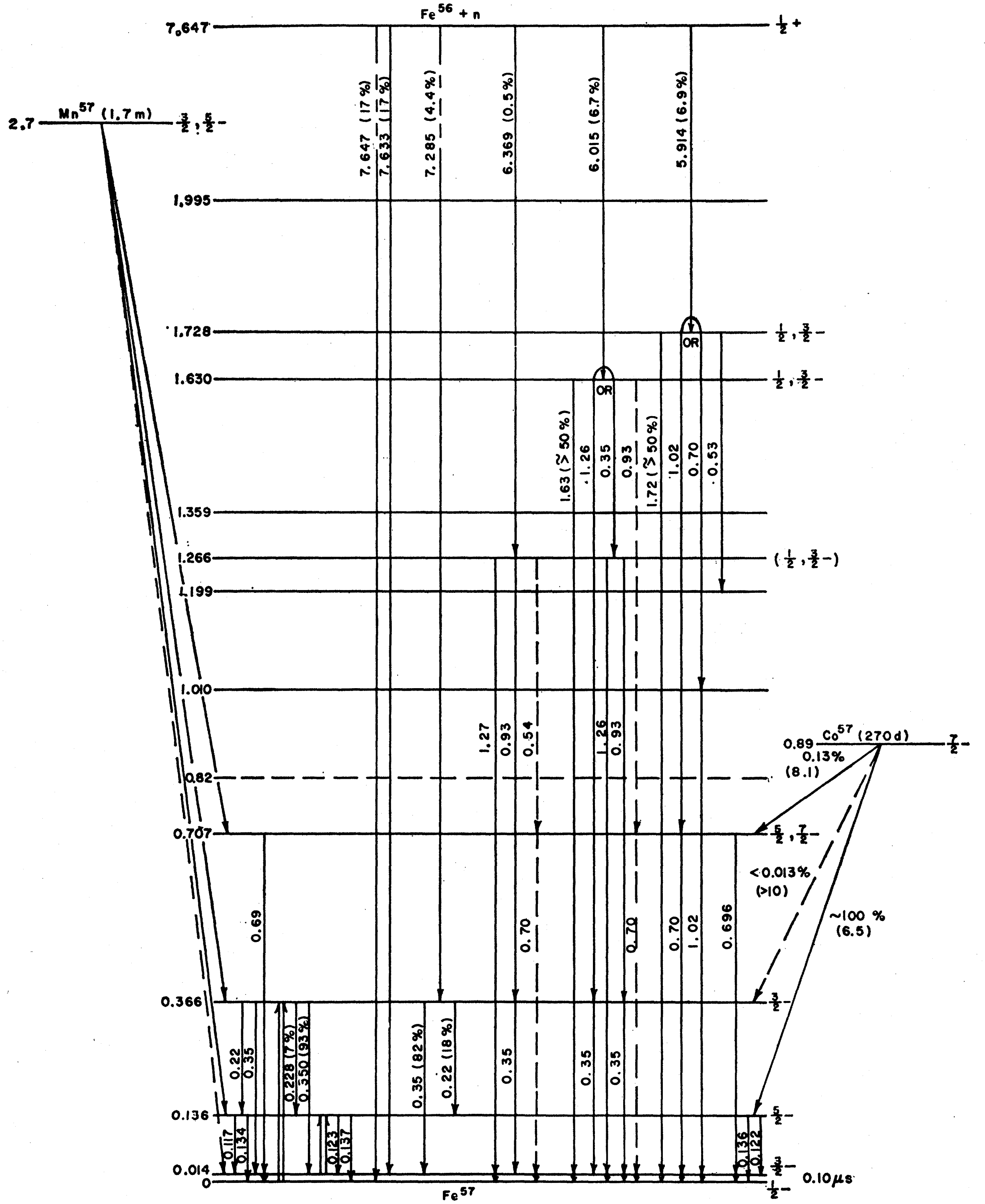

FIG. 5. Energy-level diagram containing most of the information known about the low-lying levels of Fe^{57}. The level energies are from references 4 and 5; the capture gamma-ray cascades are from the present work; the Co^{57} decay is from the present work and reference 15; the Mn^{57} decay from reference 14; and the Coulomb excitation from references 12 and 13. The positions of the neutron capturing state and the ground state of Mn^{57} are not to scale.

intensity of transitions from the 1.630-Mev level. In the existing level scheme, the 1.26-Mev transition can represent a transition from the 1.630-Mev level to the 0.366-Mev level, or alternately, de-excitation of the 1.266-Mev level following a 0.364-Mev transition from the 1.630-Mev level (cf. Fig. 5). In the latter case a certain amount of ~0.90-Mev radiation would also be emitted. The first possibility is regarded as the more probable. It is uncertain whether the 0.70-Mev gamma ray seen in part (a) is entirely due to overlapping with the stronger gamma ray seen in part (b), or whether there may actually be a weak cascade from the 1.630-Mev level through the 0.707-Mev level.

5.914 Mev

In part (b) of Fig. 5 peaks are seen with energies of 0.35, 0.53, 0.70, 0.91, 1.02, and 1.72 Mev. The 1.72-Mev gamma ray corresponds to a transition to the ground state or first-excited state. It appears to account for somewhat more than half of the total intensity of transitions from the 1.728-Mev level. The 0.70- and 1.02-Mev gamma rays fit cascades through either the 1.010- or 0.707-Mev levels. The 0.53-Mev gamma ray fits in the existing level scheme only between the 1.728- and 1.199-Mev levels, and we tentatively place a transition between these two levels. There is not sufficient evidence in the present work to establish the decay modes of the 1.199-Mev level.

The 0.35-Mev peak in part (b) of Fig. 4 is considered to be due largely to overlapping with the spectrum coincident with the 6.015-Mev gamma ray. Thus in the de-excitation of the 1.630- and 1.728-Mev levels the 0.366-Mev level is populated chiefly by transitions from the 1.630-Mev level and the 0.707 (or 1.010) Mev level by transitions from the 1.728-Mev level.

In the decay scheme of Fe^{57} constructed by Ad'yasevich, *et al.*,[8] a 1.53-Mev transition was placed between the 1.728- and 0.136-Mev levels. There is no evidence in the present results for a transition of this energy from the 1.728-Mev level.

DISCUSSION

The results of the present work, together with relevant data from other studies involving Fe^{57} are shown in Fig. 5. We now proceed to some detailed comments about the decay scheme.

0.366-Mev Level

The decay of Mn^{57} to this state via an apparently allowed transition,[14] fixes its parity as odd. The Coulomb excitation of the state thus is *E*2, limiting its spin and parity to $\frac{3}{2}-$ or $\frac{5}{2}-$. Following Coulomb excitation this state was found to decay primarily to the $\frac{3}{2}-$ first-excited state with a weak branch to the $\frac{5}{2}-$ second-excited state, rather than to the $\frac{1}{2}-$ ground state, and accordingly, the $\frac{5}{2}-$ alternative was proposed.[12] However, all other evidence indicates $\frac{3}{2}-$ character for this level: Its spin is $\frac{3}{2}$ as determined by angular correlation studies.[10] There is a strong capture gamma ray transition to it from the $\frac{1}{2}+$ level formed in thermal neutron capture[8,9] and no electron capture transition to it from the $\frac{7}{2}-$ ground state of Co^{57}. This raises the question of the possible existence of two levels in the vicinity of 0.366 Mev, one populated by Coulomb excitation and the other by thermal neutron capture. However, the results of the present experiment show that the de-excitation of the 0.366-Mev level populated by thermal neutron capture is similar to that of the level in this vicinity reached by Coulomb excitation. We conclude, therefore, that there is only one state at this energy and that its spin and parity are $\frac{3}{2}-$. The absence of a strong ground-state transition is unexplained.

0.707-Mev State

This level is also fed by an apparently allowed transition[14] from Mn^{57}, which fixes its parity as odd. The intensity of the electron capture decay branch of Co^{57} to this state is too great to represent a second forbidden transition, and therefore its spin and parity are $\frac{5}{2}-$, $\frac{7}{2}-$, or $\frac{9}{2}-$. It decays to the ground state–first-excited state doublet, limiting its possible spins to $\frac{5}{2}$ or $\frac{7}{2}$. Because the ground state and first-excited state are separated by only 0.014 Mev and because of the uncertainties in the energies of the 0.707-Mev level and the transition de-exciting it, it is not certain whether this transition proceeds to the first-excited state or to the ground state. Neither can the existence of transitions to both levels be ruled out. Both the measured gamma-ray energy, 0.696±0.004 Mev, and the choice of spins for the 0.707-Mev level favor a transition to the first-excited state.

Higher States

The information about the decay of the 1.266, 1.630, and 1.728 Mev states is certainly incomplete. However, the main features of the decay of these states have been established. Precision energy measurements in the region below 2 Mev of Fe capture gamma rays would be most helpful in resolving some of the remaining ambiguities.

Co^{57} Decay

The most unusual feature in the Co^{57} decay is the high logft value for the allowed transition to the 0.707-Mev state indicating a possible forbiddenness. The main decay to the 0.136-Mev state also appears to be somewhat inhibited.

The confirmation of the decay of Co^{57} to the 0.707 Mev level of Fe^{57} indicates that the Co^{57} total disintegration energy of 0.57 Mev reported from an inner bremsstrahlung measurement[16] is not correct and that the value of 0.89 Mev determined from the $Fe^{57}(p,n)Co^{57}$ reaction[17] should be adopted.

Mn^{57} Decay

The decay of this nucleus to the $\frac{5}{2}-$ second-excited state and the $\frac{3}{2}-$ third-excited state establishes Mn^{57} to be $\frac{3}{2}-$ or $\frac{5}{2}-$. From the coupling behavior of individual nucleons in the $(f_{7/2})^{-3}$ configuration found in neighboring nuclei, the higher spin is considered to be more probable. The log*ft* values for the various decay modes cannot be determined until the strength of the branch to the $\frac{3}{2}-$ first-excited state is measured.

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Coincidence Studies of the Thermal Neutron Capture Gamma Rays of Chromium*

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The gamma-ray cascades which follow thermal neutron capture in chromium have been investigated by means of the measurement of coincidences between gamma rays detected by a three-crystal pair spectrometer and a single NaI crystal. Samples of normal chromium and chromium enriched in Cr^{50} and Cr^{53} were used. The following assignments of gamma rays to individual isotopes have been made. Cr^{51}: 8.499, 7.36, 6.34, 6.12, 5.46, and 5.18 Mev; Cr^{53}: 7.929, 7.36, 5.61, and 5.26 Mev; Cr^{54}: 9.716, 8.881, 7.097, 6.872, 6.644, 6.31, 6.00, and 4.83 Mev. A number of features of the de-excitation of the energy levels populated by these transitions are established.

INTRODUCTION

THERE are four stable isotopes of chromium, three of which contribute appreciably to the total thermal neutron capture cross section. The abundances,[1] cross sections,[1] and contributions of these isotopes to the total cross section are listed in Table I.

The thermal neutron capture gamma rays of normal chromium have been studied by Kinsey and Bartholomew[2] with the aid of a pair spectrometer, by Groshev and co-workers[3] with the aid of a Compton recoil spectrometer, and by Braid[4] and Reier and Shamos[5] with the use of scintillation techniques. The results of these four groups are summarized in Table II.

TABLE I. Properties of the chromium isotopes.

Isotope	Abundance (percent)[a]	Capture cross section (10^{-24} cm^2)[a]	Contribution to cross section (percent)
Cr^{50}	4.31	17.0	23.6
Cr^{52}	83.76	0.76	20.4
Cr^{53}	9.55	18.2	55.8
Cr^{54}	2.38	<0.3	<0.3

[a] See reference 1.

Because of the contributions of three isotopes to the capture-gamma-ray spectrum of chromium, it has not previously been possible to assign with certainty more than a few of these gamma rays to individual isotopes of chromium, despite the existence of other information from studies of nuclear reactions and the decay of radioactive nuclei. In the present experiment the capture gamma rays produced in samples enriched in Cr^{50} and Cr^{53} and normal chromium placed in a thermal neutron beam have been investigated with the use of a three-crystal pair spectrometer in coincidence with a single scintillation detector. By this method most of the known capture gamma rays of chromium have

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