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FOREWORD

This group of reprints of papers published in *The Physical Review* during the year is submitted as a progress report for the year 1955.

The study of nuclear-energy levels is being continued both in the Physics Department of the University and at the Argonne National Laboratory, under their Participating University Program.

J. M. Cork

J. M. Cork

TABLE OF CONTENTS

I

RADIOACTIVITIES OF Zn^{69} AND Zn^{71}

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Radioactivities of Zn^{69} and Zn^{71}

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(Received October 22, 1954)

The beta and gamma rays emitted in the decay of Zn^{69} and Zn^{71} have been studied with a ten-channel coincidence scintillation spectrometer. The previous assignments of a 435-kev isomeric transition to the 14-hr Zn^{69} activity and a 900-kev beta ray to the 1-hr Zn^{69} activity were confirmed. In addition to the 2.2-min activity of Zn^{71}, a previously unreported 3-hr activity of Zn^{71} was detected. A beta ray with an end-point energy of 2.4 ± 0.2 Mev and gamma rays with energies of 0.12, 0.51, 0.90, and 1.09 Mev were detected and assigned to the 2.2-min activity. A beta ray with an end-point energy of 1.5 ± 0.1 Mev and gamma rays with energies of 0.38, 0.49, and 0.61 Mev were detected and assigned to the 3-hr Zn^{71} activity. It was established that each of the gamma rays in the 3-hr activity is in coincidence with the other two gamma rays as well as the 1.5-Mev beta ray. Decay schemes for the two Zn^{71} activities are proposed.

THE short-lived activities produced by neutron capture in zinc have been previously studied with varying degrees of completeness. The 14-hr and 52-min activities of Zn^{69} had been investigated in some detail, whereas the 2.2-min activity of Zn^{71} had been examined only by absorption and half-life studies. Zn^{69} had been found to have a metastable state which decays with a 14-hr half-life by the emission of a 436-kev[1,2] $M4$ transition[3] to the ground state of Zn^{69}. The ground state then decays with a 52-min half-life[4] to the ground state of Ga^{69}. The beta ray emitted by the 52-min state had been found[3] to have a maximum energy of about 900 kev.

The 2.2-min activity of Zn^{71} was first produced by Hughes *et al.*[5] by neutron capture in normal Zn. By aluminum absorption experiments they determined the maximum energy of the beta rays associated with this activity to be 2.1 Mev. They measured the cross section for thermal neutron capture in Zn^{70} to be about 0.09 barn.

According to the nuclear shell theory, there should exist a metastable state in Zn^{71} similar to the one in Zn^{69}. One should then expect to find a second activity in the Zn^{71} and possibly an isomeric transition between the two states.

ELEMENT	MASS NUMBER 64	65	66	67	68	69	70	71
Cu		31% ↓						
Zn	49%	(250D)	28%	4%	18%	(14H → 1H)	0.6%	(2M | 3H) ↓↓
Ga						60%		40%
Enriched Zn	10%		8%	4%	29%		48%	

FIG. 1. The relative abundance of the Zn isotopes.

* University of Michigan, Ann Arbor, Michigan.
[1] A. Guthrie, Phys. Rev. **60**, 746 (1941).
[2] B. D. Nag-Chowdhury, Proc. Nat. Inst. Sci. India **10**, 317 (1944).
[3] R. B. Duffield and L. M. Langer, Phys. Rev. **89**, 854 (1953).
[4] J. J. Livingood and G. T. Seaborg, Phys. Rev. **55**, 457 (1939).
[5] Hughes, Wallace, Goldfarb, Eggler, Murcock, and Goldstein (unpublished).

The present investigation is concerned mainly with the study of Zn^{71}. A preliminary report[6] was presented at the Detroit meeting of the American Physical Society. The sources were obtained by the neutron irradiation of both normal Zn and enriched Zn^{70}. The relative abundance of the Zn isotopes in both normal Zn and enriched Zn^{70} are illustrated in Fig. 1. Since in the enriched sample, Zn^{70} is enriched by a factor of 80, whereas Zn^{68} is only enriched by a factor of 1.7 and all other isotopes are depleted, one can conclude that any activity which is observed in the enriched samples but not in the normal Zn samples is to be assigned to Zn^{71}.

The sources were examined with a ten-channel scintillation coincidence spectrometer.[7] In all, four activities were found in the enriched Zn^{70} samples. They had half-lives of 2.2 min, 1 hr, 3 hr, and 14 hr.

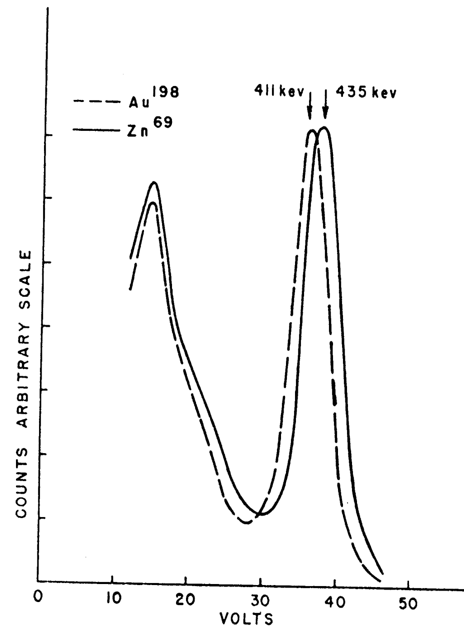

FIG. 2. The NaI(Tl) pulse height distributions of Zn^{69} (14-hr) and the 411-kev gamma-ray of Au^{198}.

[6] LeBlanc, Cork, and Burson, Phys. Rev. **94**, 1436(A) (1954).
[7] S. B. Burson and W. C. Jordan, Phys. Rev. **91**, 498 (1953).

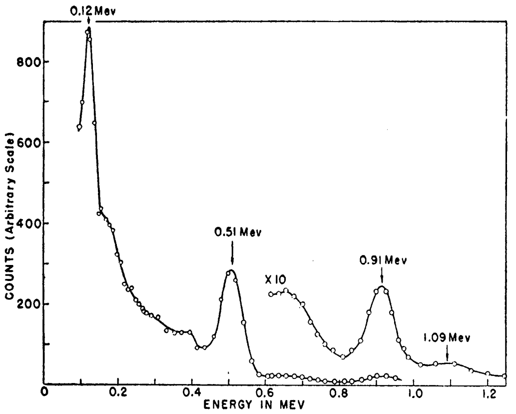

FIG. 3. Zn^{71} (2.2-min) NaI(Tl) pulse-height distribution.

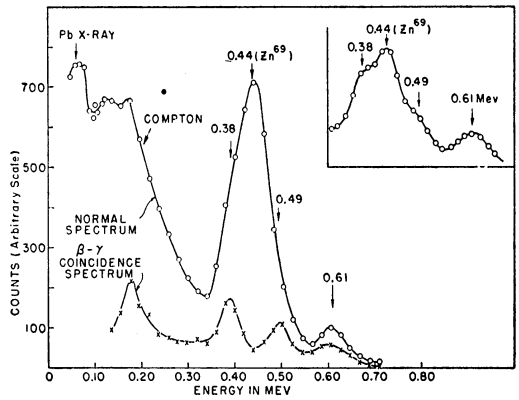

FIG. 4. Zn^{71} (3-hr) NaI(Tl) pulse-height distribution.

Of these, only the 1-hr and 14-hr activities were detected in the normal Zn sources and are thus identified as the previously reported activities of Zn^{69}. The 2.2-min and 3-hr activities must then be due to Zn^{71}. Since the Ga^{71} which is formed by the beta decay of Zn^{71} is stable, the fact that two activities are associated with Zn^{71} implies that one of them must be due to a metastable state in Zn^{71}.

Since the Zn^{69} activities appeared to some extent in all of the samples, it was necessary to examine their photon spectra, coincidence spectra, and beta rays in order that they might be easily identified in the presence of the radiations from Zn^{71}.

1. 14-Hr ACTIVITY OF Zn^{69}

The NaI pulse-height distribution from the gamma rays of the 14-hr decay is shown in Fig. 2. The figure also contains the pulse-height distribution from the 411-kev gamma ray emitted in the decay of Au^{198}. Figure 2 is interpreted to indicate that only one gamma ray is associated with the 14-hr activity and that it has an energy of about 435 kev. In addition, it was established that the 435-kev gamma ray is not in coincidence with beta rays. This confirms the previous assignment of the 14-hr activity to the metastable state.

2. 52-MIN ACTIVITY OF Zn^{69}

There were no gamma rays detected which could be assigned to this activity. Very strong beta rays were observed, and their maximum energy was measured by aluminum absorption experiments to be about 0.85 Mev. This agrees with previous measurements.

3. 2.2-MIN ACTIVITY OF Zn^{71}

Samples of the 2.2-min activity of Zn^{71} were produced by the irradiation of enriched Zn^{70} for periods of about 5 minutes. The half-life of the radioactivity from these samples was measured to be about 2.2 min, in good agreement with previous results. The gamma-ray spectrum was obtained by means of the scintillation spectrometer and is shown in Fig. 3. The photopeaks for four gamma rays are identified and found to decay with the 2.2-min half-life. Their energies are 0.12, 0.51, 0.90, and 1.09 Mev. The 0.51- and 0.12-Mev gamma rays are by far the most intense ones in the spectrum. The results of gamma-gamma coincidence measurements, however, show that the 0.51- and 0.12-Mev transitions are not in coincidence with each other. The 0.90- and 1.09-Mev transitions were too weak for one to be able to obtain reliable gamma-gamma coincidence measurements with them.

It was established that all of the gamma rays are in coincidence with beta rays. The results of aluminum absorption experiments on the beta rays indicate a maximum beta-ray energy of 2.4 ± 0.2 Mev. The slope of the aluminum absorption curve for the beta rays in coincidence with the 0.51-Mev gamma ray is not significantly different from that of the absorption curve for single counts. Because of the rapid decay of the sample, however, statistics of the absorption data are not good enough to allow one to determine if there is any branching to the ground state.

4. 3-Hr ACTIVITY OF Zn^{71}

The 3-hr activity which was detected in this investigation and assigned to Zn^{71} had not been previously observed. Even with enriched isotopes, it was not possible to obtain the 3-hr activity without the presence of strong 1-hr and 14-hr activities of Zn^{69}.

The NaI(Tl) pulse-height distribution obtained from the gamma rays of the 3-hr activity of Zn^{71} is shown as the top curve in Fig. 4. The photopeak of the 0.435-Mev transition of Zn^{69} is the dominant feature of the distribution; however, another photopeak is clearly resolved at 0.61 Mev. In addition, the 0.435-Mev photopeak is distorted on both the low- and high-energy sides, indicating the possibility of more gamma rays being present. This region of the spectrum was examined with better resolution and the results are shown in the inset of Fig. 4. It is clear, from these data, that the peak at about 0.44 Mev is complex. In order to examine this region without the presence of the Zn^{69} gamma ray, the pulse-height distribution of gamma rays which are in coincidence with beta rays was determined (see bottom curve of Fig. 4). The peaks which occur in this spectrum at 0.38, 0.49, and 0.61 Mev are interpreted as photopeaks of gamma rays of these energies. The peak at about 0.17–0.20 Mev is interpreted as due to Compton electrons and Compton-scattered gamma rays. The rate of decay of each of these peaks was determined and found to correspond to a half-life of about 3 hr.

The source was allowed to decay for one day, and then another normal pulse-height distribution was determined. The only activity which remained was that of the 14-hr Zn^{69}. This pulse-height distribution was then normalized, at the 0.44-Mev peak, to the pulse-height distribution of the previous day and subtracted from it. The resulting distribution was the same as that of the gamma rays in coincidence with beta rays which was obtained the first day. Thus, it is concluded that all of the gamma rays which were found in the 3-hr activity are in coincidence with beta rays.

The maximum energies of the beta rays which are in coincidence with the 0.38, 0.49, and 0.61-Mev gamma rays were determined by measuring the attenuation of the beta rays in aluminum. It was established that each gamma ray is in coincidence with a single beta ray whose maximum energy is 1.5 ± 0.1 Mev in each case. This strongly suggests that the three gamma rays are in cascade.

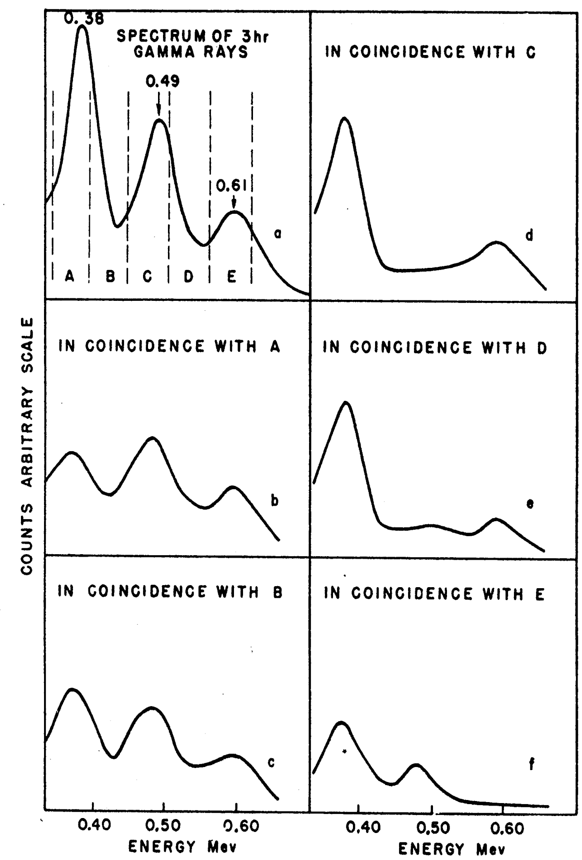

FIG. 5. Zn^{71} (3-hr) gamma-gamma coincidences.

Gamma-gamma coincidence experiments were performed with the three gamma rays in this decay. The results are shown in Fig. 5. The positions of the three gamma-ray photopeaks in the pulse-height distribution were determined from the beta-gamma coincidence pulse-height distribution shown in Fig. 5(a). The single-channel analyzer was then set to cover one of the regions bounded by the dotted lines, and the ten-channel analyzer swept across the 0.30- to 0.65-Mev region of the distribution. The resulting coincidence distributions are shown as curves *b*, *c*, *d*, *e*, and *f* in Fig. 5. It can be seen from these curves that each gamma ray is in coincidence with the other two; thus, the three transitions are in cascade.

5. DECAY SCHEME OF Zn^{71}

The present investigation has confirmed the prediction of the nuclear shell theory that a metastable state should exist in Zn^{71}. It has not been possible, however, to determine from the data which of the two activities is due to the ground state. For this reason the suggested decay schemes of the two activities are shown separately. See Fig. 6. The decay scheme of the 3-hr activity is strongly supported by the beta-gamma and gamma-gamma coincidence measurements. There is no information to indicate in what order the three gamma rays are emitted; the lowest energy transition is arbitrarily placed at the bottom.

The portion of the decay scheme of the 2.2-min state which is indicated by solid lines is confirmed by coincidence measurements. The portion of the level scheme represented by dashed lines is based entirely on the energies of the transitions. The energy of the 1.09-Mev gamma ray does not agree very well with the sum of the 0.12- and 0.91-Mev transitions. This is not considered to be a serious objection since the accuracy of measurement of the energy of the 1.09-Mev transition is rather poor, due to the very low intensity of the peak. There may be additional beta transitions to the 0.12-Mev level and to the ground state.

It is difficult to understand why there are no common states in Ga^{71} in the two decay schemes. One might

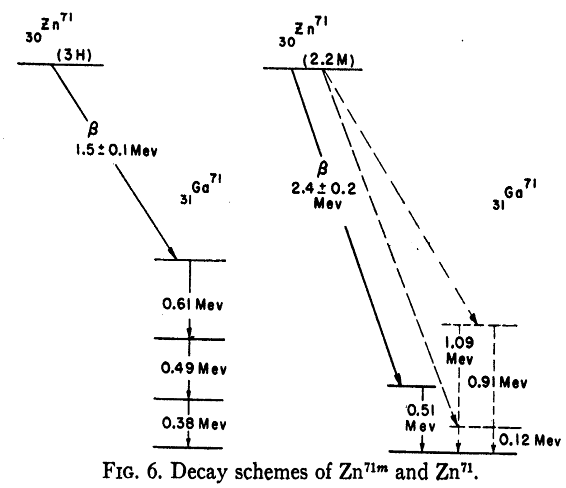

FIG. 6. Decay schemes of Zn^{71m} and Zn^{71}.

suspect that the 0.49-Mev transition which follows the 3-hr beta decay is the same as the 0.51-Mev transition in the 2.2-min decay. In order to check this, the energies of the two transitions were compared without altering the spectrometer settings. It was determined that there were indeed two distinct gamma rays with energies that differed by about 0.03 Mev. The absence of common states in the two decay schemes might be due to some selection rule other than those arising from the conservation of total spin and parity.

The total energy of the Zn^{71} decay is measured to be about 2.9 Mev. This value is in good agreement with that predicted from the beta decay systematics.[8]

[8] K. Way and M. Wood, Phys. Rev. **94**, 119 (1954).

II

DECAY OF THE 3.5-min METASTABLE STATE OF Sb^{122}

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Decay of the 3.5-min Metastable State of Sb^{122}

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(Received November 4, 1954)

The radiations associated with the 3.5-min activity of Sb^{122} have been studied with 180° magnetic photographic spectrometers and a ten-channel coincidence scintillation spectrometer. Two gamma rays with energies of 60.7 and 75.3 kev were detected by means of internal conversion electrons and also by means of the scintillation spectrometer. The 75.3-kev transition is the more strongly converted of the two, and it is concluded that it is the isomeric transition. The two gamma rays are emitted in cascade.

AN isomeric state in Sb^{122} was first reported by der Mateosian *et al.*[1] in 1947. They measured its half-life to be 3.5 min. The gamma rays associated with the 3.5-min decay have been investigated by two groups, one employing a scintillation spectrometer[2] and the other an ionization chamber.[3] The results of the scintillation spectrometer study indicated the presence of one gamma ray with an energy of 68 kev, whereas

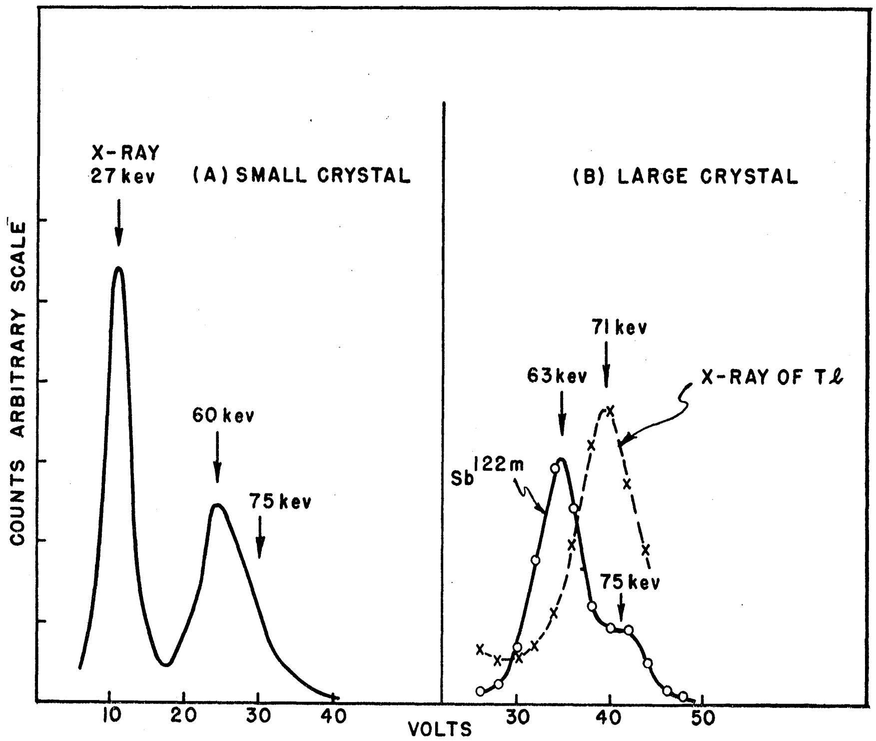

FIG. 1. NaI(Tl) pulse-height distributions of gamma rays from Sb^{122m}.

* University of Michigan, Ann Arbor, Michigan.
[1] der Mateosian, Goldhaber, Muehlhause, and McKeown, Phys. Rev. **72**, 1271 (1947).
[2] E. der Mateosian and M. Goldhaber, Phys. Rev. **82**, 115 (1951).
[3] J. H. Kahn, Oak Ridge National Laboratory Unclassified Report ORNL-1089, Nov. 1951 (unpublished).

TABLE I. Internal conversion electrons associated with the decay of Sb^{122m}.

Electron line energy (in kev)	Interpretation	Energy sum (in kev)
30.2	K^1	60.7
45.1	K^2	75.6
70.2	L_I^2	74.9
70.9	L_{III}^2	75.0

the results of the ionization chamber study indicated the presence of two gamma rays with energies of 59 and 74 kev.

The Sb^{122m} sources which were used in the present investigation were obtained by the irradiation of enriched Sb^{121} in the Argonne Heavy Water Reactor (CP-3′). They were examined with both 180° magnetic photographic spectrometers[4] and a ten-channel coincidence scintillation spectrometer.[5] Four internal conversion electron lines were detected with the 180° spectrographs. They are listed in the first column of Table I. They are interpreted as internal conversion electrons from gamma rays with energies of 60.7 and 75.3 kev. The electron lines for the 75.3-kev gamma ray are much stronger than the K line of the 60.7-kev transition.

The NaI pulse-height distribution produced by the gamma rays from Sb^{122m} is shown in Fig. 1(a). The peaks decayed with a half-life of about 3.3 min. The low-energy peak, at about 27 kev, is due to the x-rays of Sb. The other peak is quite broad and is distorted on the high-energy side, indicating that it is due to more than one gamma ray. This peak was examined with better resolution and the resulting distribution is shown in Fig. 1(b). The strong component of this peak occurs at about 63 kev, and the distortion of the high-energy side indicates the presence of a gamma ray with an energy in the neighborhood of 75 kev. This agrees with the internal conversion data.

The photopeak of the 75-kev gamma ray is considerably weaker than that of the 60-kev transition. Since the internal conversion electron lines of the 75-kev transition were stronger than those of the 60-kev gamma ray, one concludes that the 75-kev radiation is the more strongly converted of the two. The 75-kev gamma ray is therefore identified as the isomeric transition. From the energy lifetime relations for gamma rays, it is concluded that the 75-kev radiation has a multipolarity of 3.

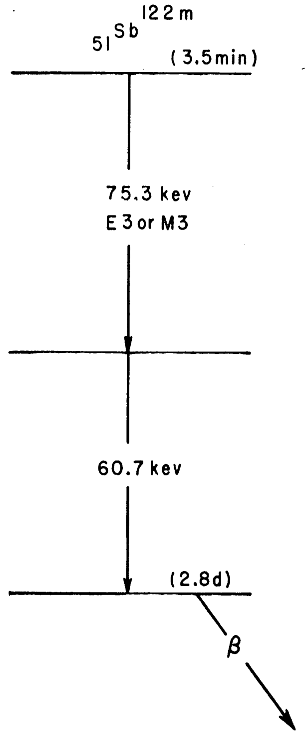

FIG. 2. The decay scheme of $_{51}Sb^{122m}$ (3.5-min).

Coincidences were observed between the x-ray and the 60–75-kev peak. Since the x-rays are produced as a consequence of the internal conversion of one of the gamma rays, one should not observe x-ray gamma-ray coincidence unless the two gamma rays are in cascade.

It is concluded from these experiments that the 3.5-min metastable state decays by means of a 75-kev isomeric transition which is followed by a 60-kev transition as shown in Fig. 2.

[4] H. Keller, and J. M. Cork, Phys. Rev. 84, 1079 (1951); Rutledge, Cork, and Burson, Phys. Rev. 86, 775 (1952).

[5] S. B. Burson and W. C. Jordan, Phys. Rev. 91, 498 (1953).

III

RADIATIONS FROM Ce^{143} (33 hr)

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Vol. 99, No. 2, 670, July 15, 1955

Radiations from Ce^{143} (33 hr).* D. W. MARTIN, J. M. CORK, AND S. B. BURSON, *Argonne National Laboratory.*—The radiations from Ce^{143} (33 hr) have been studied with the scintillation coincidence spectrometer and with magnetic photographic spectrographs. Enriched Ce^{142} was irradiated with reactor neutrons. Gamma rays of 1.10 ± 0.01, 0.861 ± 0.005, 0.724 ± 0.002, 0.668 ± 0.002, 0.565 ± 0.005, 0.493 ± 0.002, 0.351 ± 0.001, 0.294 ± 0.001, 0.232 ± 0.001, and 0.0574 ± 0.0002 Mev are found to decay with the 33-hr period in the NaI(Tl) pulse-height distribution. Conversion lines are seen for all but the 1.10- and 0.57-Mev transitions. Gamma-gamma and beta-gamma coincidence data define the decay scheme with considerable certainty. The Pr^{143} nucleus is shown to have excited states at 0.0574, 0.232 (or 0.493), 0.351, 0.724, 0.918, and 1.16 Mev. Qualitative observations of the beta-ray components were made by observing the pulse-height distributions from an anthracene crystal in coincidence with the principal gamma components. In addition to the known strong components at 1.38, 1.09, and 0.71 Mev, two distinct weak components at $\sim$0.5 and $\sim$0.3 Mev are observed, coincident with radiations from the 0.918- and 1.16-Mev levels respectively. The pulse distribution coincident with the 57-kev gamma ray is indistinguishable from the non-coincidence distribution above 1 Mev. Thus, the 1.38-Mev beta ray feeds the 58-kev level, and any ground-state beta transition is of low intensity.

* Work done under auspices of U. S. Atomic Energy Commission.

IV

ENERGIES OF THE RADIATIONS FROM Co^{57} AND Co^{58}

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Energies of the Radiations from Co^{57} and Co^{58}†

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(Received March 28, 1955)

Using magnetic and scintillation spectrometers the energies of the radiations from Co^{57} and Co^{58} have been evaluated. Several gamma rays not previously reported have been observed. Co^{57} decays mainly by K capture but also to a slight extent by positron emission with an upper energy limit of about 300 kev, followed by gamma rays with energies 14.6, 29, 99.8, 122.8, 137.4, and 700 kev. Co^{58} decays by K capture and with positron emission of upper energy 485±10 kev. Gamma rays with energies of 814 and 500 and possibly 1300 kev accompany the decay.

As early as 1937 it was found[1] that iron bombarded with deuterons in the cyclotron yielded several long-lived cobalt radioactivities. Subsequent investigations[2] resulted in the assignment of activities with half-lives of 270 and 72 days to Co^{57} and Co^{58}, respectively. The reports on the energies of the radiations show considerable disagreement indicating a need for further study.

In the present investigation magnetic photographic, and scintillation spectrometers were employed to study gamma rays, and the double-focusing, magnetic spectrometer was used to observe the positron spectrum of Co^{58}. In addition to the gamma energies previously recorded certain gamma transitions not previously reported are observed. The Co^{57} source was obtained from the Oak Ridge National Laboratory and was produced by a $p,2n$ reaction on Ni^{58} in a target of ordinary nickel. The resulting Cu^{57} in turn decays by positron emission through Ni^{57} to Co^{57} and thence to Fe^{57}. The Co^{58} specimen was from the same source but produced in the reactor by the (n,p) reaction on Ni^{58}. It decays mainly by K capture but also by weak positron emission to Fe^{58}.

COBALT-57

Some of the previously reported energies for the three well-known gamma rays, together with the results of the present investigation, are shown in Table I. In addition to these three gamma rays, others appear with energies of 700, 99.8, and 29 kev. These additional gamma rays are observed with the scintillation spectrometer. Of them, only the 99.8-kev gamma appears by conversion and this with a single line assumed to be due to Fe K-electrons.

For the three gamma rays shown in Table I, many electron lines are observed whose energies and relative intensities are shown in Table II. The relative intensities for the lines due to the 14.6-kev gamma ray are from visual estimates of the photographic densities, corrected for variation in radius and sensitivity of the emulsion with energy. The intensities for the other two gamma rays were obtained both by microphotometer traces of the photographic plates and by comparing the resolved peaks obtained with the source in the double-focusing spectrometer. The 14.6-kev in Fe^{57} has been reported[3] to have a half-life of 1.1×10^{-7} sec and the transition to the ground state was assumed[4] to be $M1$. The Z^2/W for this radiation is 46.2. From the empirical summary of Goldhaber and Sunyar, the observed K/L ratio of 3 appears to be somewhat lower than expected for an $M1$ transition. It would seem to be more compatible with an $E1$ or an $M2$ transition. The lifetime for the $M2$ transition at this energy would be of the order of seconds and this designation is thus improbable.

The large values of the K/L ratios for the 122.8- and 137.4-kev gamma rays suggest $E1$, $E2$, $M1$, or $M2$ transitions. The half-life of the $M2$ transition would

TABLE I. Gamma energies of Co^{57} as reported, in kev.

Observer	P[a]	ED[b]	DW[c]	AG[d]	CM[e]	Present work
γ_1	117	119		122.8	119	122.8
γ_2	130	131		137.6	133	137.4
γ_3			14			14.6

[a] E. H. Plesset, Phys. Rev. 62, 181 (1942).
[b] E. Elliott and M. Deutsch, Phys. Rev. 64, 321 (1943).
[c] M. Deutsch and W. Wright, Phys. Rev. 77, 139 (1950).
[d] D. Alburger and M. Grace, Proc. Phys. Soc. (London) A67, 280 (1954).
[e] B. Craseman and D. Manley, Phys. Rev. 98, 279 (A) (1955).

TABLE II. Energy and relative intensity of electron conversion lines from Co^{57}.

Designation	Electron energy, kev	Relative intensity	Energy sum, kev
K_1	7.3	3	14.4
L_1	13.7	1	14.6
M_1	14.5	0.25	14.6
K	92.7		99.8
K_2	115.7	10	122.8
L_2	121.8	0.9	122.7
M_2	122.7	0.15	122.8
K_3	130.3	8	137.4
L_3	136.6	0.8	137.5

† This investigation received the joint support of the U. S. Atomic Energy Commission and the Office of Naval Research.

[1] Livingood, Seaborg, and Fairbrother, Phys. Rev. 52, 135 (1937).
[2] Hollander, Perlman, and Seaborg, "Table of Isotopes," Berkeley (1952).
[3] M. Deutsch and W. Wright, Phys. Rev. 77, 139 (1950).
[4] M. Goldhaber and A. Sunyar, Phys. Rev. 83, 906 (1951).

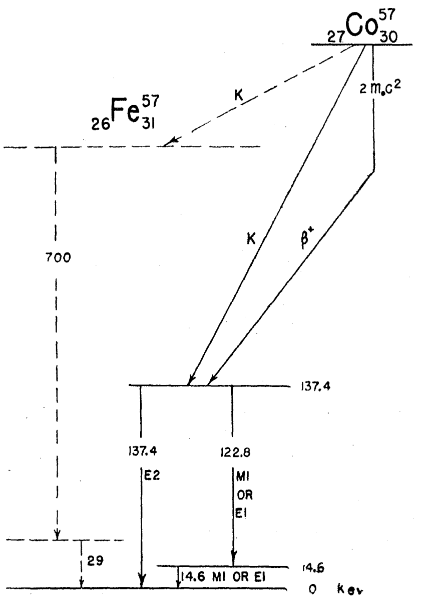

FIG. 1. Nuclear level scheme for Fe^{57}.

still be of the order of a thousandth of a second and hence should probably be excluded. While the K-conversion lines for the two gamma rays are of the same order of darkness and their K/L ratios are about the same, it is observed that the unconverted peak at 122.8 kev is many times[5] stronger than the peak at 137.4 kev. Hence, if the absolute conversion coefficient for the 137-kev gamma ray is ten times that for the 123-kev gamma ray, then the former is probably due to an $E2$ and the latter to an $E1$ or $M1$ transition. The positron spectrum was found to be extremely weak, with an upper limit of about 300 kev. It was not resolved into the two components reported.[6]

The 29-kev peak was found to be in coincidence with both the 100- and 700-kev radiations but not with the 123- or 137-kev gammas. No coincidences could be observed between the 700- and the 100-, 123-, or 137-kev radiations. It should be noted that coincidences as observed might result from the iodine x-ray (28 kev) escaping from one crystal back to the opposite crystal, resulting in an apparent peak due to the true peak energy minus the x-ray energy. Evidence that the low-energy peak is a gamma ray comes from the fact that it appears in the "singles" curve when there is no idoine or other scatterer back of the source. When iodine is intentionally placed directly back of the source the peak shifts slightly toward lower energy. Moreover, the 100-kev gamma ray yields a conversion line. The weak 700-kev transition probably follows K capture, and from the coincidence observation it might be concluded that it terminates at a level other than the ground state although this evidence is not incontrovertible. The escape peak is less likely to be significant at this high energy. The well-established transitions are shown as heavy lines in the nuclear level scheme of Fig. 1. The 99.8-kev transition is not included.

The half-life of the Co^{57} sample observed over a period of 8 months appears to be 267 days.

COBALT-58

Co^{58} decays by both K capture and positron emission to Fe^{58}. A single gamma ray of energy 0.81 Mev had been reported.[2] In the present investigation this gamma ray is observed both by electron conversion and by the scintillation spectrometer. The K-conversion line has an energy of 807 kev, indicating a gamma energy of 814 kev. The L line is very weak so that the K/L ratio is exceedingly large. It is impossible to infer from this ratio the type of multipole radiation, since at this small Z^2/W (0.8), the K/L ratio is large for all types of radiation. However, the ground state for the even-even $_{26}Fe^{58}$ nucleus is undoubtedly a level of even parity and zero spin. In such nuclei the first excited state is usually one of even parity and spin 2, so that an $E2$ transition is expected.

The Co^{58} source also contains some Co^{60} with its long-lived radiation at 1.17 and 1.33 Mev. With the scintillation spectrometer, strong peaks are obtained at 500 and 800 kev, and a weaker peak at 1.3 Mev. The 500-kev peak was at first assumed to be annihilation radiation. On observing coincidences between all betas in an anthracene crystal, and the gamma distribution in a NaI crystal, the 500- and 800-kev peaks were present in about the same relative intensity. On observing gamma-gamma coincidences with one crystal

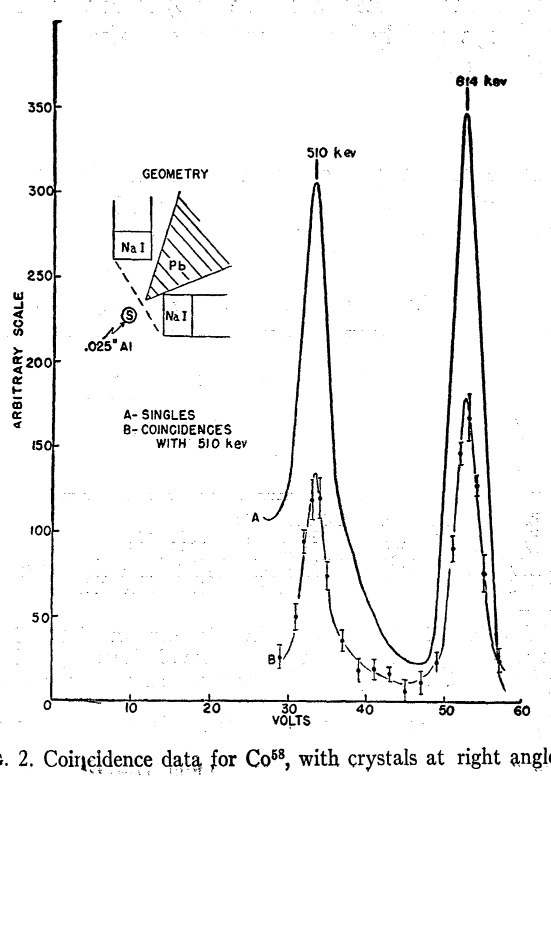

FIG. 2. Coincidence data for Co^{58}, with crystals at right angles.

[5] D. Alburger and M. Grace, Proc. Phys. Soc. (London) A67, 280 (1954).

[6] B. Craseman and D. Manley, Phys. Rev. 98, 279 (1955).

set to receive the 500-kev peak, again the other crystal noted the two peaks in the same relative intensity. Since the annihilation photons travel in opposite directions and could yield 500–500 kev coincidences, the crystals were arranged at right angles with the source as shown in Fig. 2. The singles and coincidence curves are represented by solid and dotted lines, respectively, strongly indicating the existence of a gamma ray of about 500-kev energy. The peak at 1.3 Mev could be a summation peak for the other gamma rays or represent a crossover transition, or be in part due to the slight amount of Co^{60} that is known to be present. On inserting about 2 cm of lead between source and crystal the intensity is reduced much more than would be the case if it were all 1.3-Mev radiation, with its absorption coefficient of 0.66 cm^{-1}. This indicates that it is largely

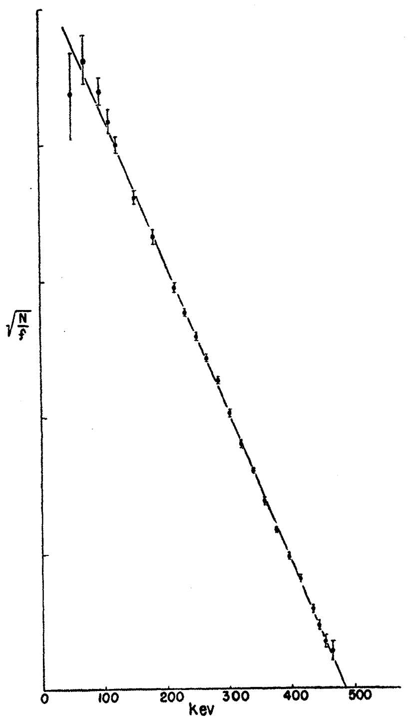

FIG. 3. The Fermi plot for the positron spectrum of Co^{58}.

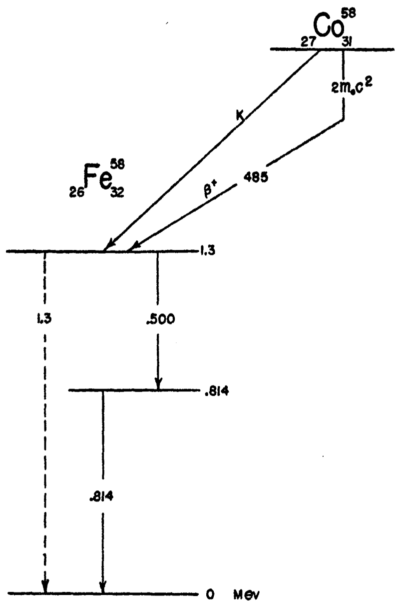

FIG. 4. Nuclear level scheme for Fe^{58}.

a summation peak, but in part it may be due to a cross-over transition.

The positron spectrum was investigated in the double-focusing spectrometer and was found to have only one component. The almost massless source consisted of a line of the carrier-free material ruled on a conducting zapon film. The spectrometer window, also of zapon, was of minimum thickness (about 15 micrograms per cm^2) to withstand a pressure difference of 6 or 7 cm of Hg. The linearity of the Fermi plot, shown in Fig. 3, down to very low energies, indicates the very small stopping power of the film. The upper energy limit is 485 ± 10 kev. If the positron decay occurs for about 15 percent of the decays, then the $\log ft$ value is about 6.5, which indicates a first forbidden transition. The simple decay scheme is shown in Fig. 4. The half-life of the Co^{58} source corrected for the presence of a slight amount of longer-lived activity is found to be 71.0 days.

V

RADIOACTIVE DECAY OF RUTHENIUM-97

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Radioactive Decay of Ruthenium-97†

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Ruthenium enriched in mass 96 was irradiated for short and long periods in the pile and the radioactivity of Ru^{97}, produced by neutron capture, was studied by magnetic and scintillation spectrometers. Several gamma rays not previously reported were found to exist. The observed gamma rays in Tc^{97}, following K capture in Ru^{97}, have energies of 109.1, 216.1, 325.1, and 570 kev. A long-lived metastable state in Tc^{97} decays by the emission of gamma rays whose conversion electrons indicate gamma energies of 90.2 and 99.2 kev. The multipolarities of most of the transitions are determined and a satisfactory nuclear level scheme is proposed.

BY the bombardment of ruthenium with both deuterons and neutrons an activity of half-life 2.8 days was observed[1] and attributed to Ru^{97}. A single gamma ray following K capture had been noted with an energy variously reported to be 0.230[1] or 0.217[2] Mev. This transition, following K capture, should occur in Tc^{97}, presumably leading to a reported[3] metastable level whose half-life has been given as 90 to 95 days. A gamma ray with an energy somewhere between 96 and 108 kev had been found to be associated with Tc^{97m}.

In the present investigation a specimen of ruthenium, enriched in mass 96 from its normal 5.7 percent up to 95.5 percent, was irradiated in the maximum flux of the Argonne heavy water pile. In order to distinguish the lines due to Ru^{97}, both short (3-day) and long (30-day) irradiations were made. Radioactive sources were studied in photographic magnetic and scintillation spectrometers. Strong electron conversion lines were observed indicating the presence of several gamma rays not previously reported. Since the separated Ru^{96} specimen contained about 1% of Ru^{102}, the well-known gamma rays for Ru^{103} were found to be present but weak. There was also a very weak iridium impurity in the separated Ru isotope, so that its well-known spectrum was faintly observed. The half-life of the Ru^{97} activity was followed through more than eight octaves and was found to be 2.44 days, or 58.6 hours.

TABLE I. Energies and relative intensities of the electron lines from Ru^{97}.

Electron energy, kev	Designation	Intensity	Energy sum, kev
15.1	Auger KL_1L_1		
15.5	Auger KL_2L_2		
17.9	Auger KLM		
20.1	Auger KMM		
69.2	$K(Tc^{97m})$		90.2
78.2	$K(Tc^{97m})$		99.2
88.1	K	3	109.1
89.0	$L(Tc^{97m})$		92.0
97.8	$L(Tc^{97m})$		100.8
106.1	L	1	109.1
195.3	K	100	216.3
213.1	L	14	216.1
215.4	M		215.9
303.9	K	8	325.0
322.2	L	1	325.2
549	K		570

The energies of the observed electron conversion lines, exclusive of those due to Ru^{103} and Ir^{192}, are presented in Table I. The interpretation of each line is given in the second column and where possible the relative intensities are presented in column 3. From these observations it can be concluded that there are at least four gamma rays associated with the 2.44-day radiation, with energies of 109.1, 216.1, 325.1, and 570 kev. These energies were also observed as peaks with the scintillation spectrometer on "singles" studies, with the exception of the 109.1, which does, however, appear in strong coincidence with the 216.1. Coincidences between the 216.1- and 325.1-kev gammas are not observed. The spectrum in coincidence with the Tc K x-rays is identical with the "singles" spectrum out to 400 kev; coincidence work with the 570-kev peak was inconclusive because of its extreme weakness. Curve A of Fig. 1 shows the "singles" spectrum and curve B shows the spectrum in coincidence with the 216.1-kev gamma ray. The photopeaks and conversion lines for these four gamma rays, observed over a period of time, all appear to die out with the same half-life. The absence of an annihilation peak at 511 kev in the scintillation spectrum and the negative result of a search for positrons with the magnetic double-focusing spectrometer indicate that Ru^{97} decays principally, if not entirely, by K capture.

In the specimen irradiated for 30 days, the long-lived Ru^{103} and the Ir^{192} electron lines appeared relatively much stronger in comparison with the lines due to the 2.44-day Ru^{97}. However, certain new lines were evident which were not due to either of the above contaminants but which appeared to have a long half-life. Successive exposures showed that after the Ru^{97} short-lived activity died out, there still remained two pairs of electron lines with energy differences characteristic

† This investigation received the joint support of the Office of Naval Research and the U. S. Atomic Energy Commission.
[1] Sullivan, Sleight, and Gadrow, Phys. Rev. **70**, 778 (1946).
[2] Mei, Huddleston, and Mitchell, Phys. Rev. **79**, 429 (1950).
[3] Hollander, Perlman, and Seaborg, *Table of Isotopes*, Berkeley, 1952 [Revs. Modern Phys. **25**, 469 (1953)].

of the K and L work functions for Tc. Figure 2 shows (a) a plate made after the 3-day irradiation, (b) one made immediately following the 30-day irradiation, and (c) one made two weeks after the 30-day irradiation, when the 2.44-day activity had largely died out. It seems likely therefore that this is the radiation previously observed[3] to be associated with a metastable Tc^{97m}, whose half-life was noted to be from 90 to 95 days. No attempt was made to verify this half-life, or that of the ground state of $Tc^{97}(\sim 10^4 Y)$.

The energies of these gamma rays are 90.2 and 99.2 kev, and their K/L conversion ratios are both approximately unity. They are of about equal intensity as judged by the density of their K conversion lines, and are both highly converted, as they hardly appear in the scintillation spectrum. The high conversion coefficient, low K/L ratio, and long half-life indicate that these are high-order multipole transitions, probably $E3$ or $M4$. According to shell theory the ground state of Tc^{97} is expected to be a $g_{9/2}$ level and the first excited state a $p_{1/2}$ level. The difference in energy of these two gamma rays, namely 9 kev, suggests the existence of two low-lying states such as $g_{9/2}$ and $7/2+$, as has been reported[4] to exist in Tc^{99m}.

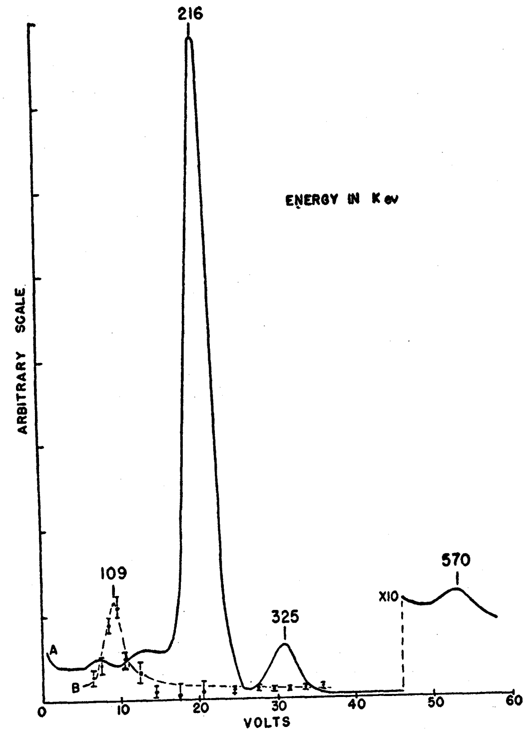


FIG. 1. Singles and coincidence spectra for Tc^{97} with the scintillation spectrometer.

The relative intensities of the electron lines associated with the 2.44-day activity were determined from microphotometer traces of the photographic plates, corrected for variations in radius and emulsion sensitivity with energy. The K/L ratios for the 109.1-, 216.1-, and 325.1-kev gammas are 3.0 ± 0.6, 7.3 ± 0.3, and 6.7 ± 0.6, respectively. The 109.1-kev gamma has a high conversion coefficient, as it appears only weakly in the scintillation spectrometer although strong conversion lines are observed. Measurements of the relative intensities of both the photopeaks and K conversion lines of the 216.1- and 325.1-kev gammas indicate that the ratio of their K conversion coefficients must be approximately unity. The fact that the 216.1-kev gamma is much stronger than the 109.1, both converted and unconverted, shows that the 216.1 follows the 109.1 and is supplied by an additional K capture branch whose degree of forbiddenness is no

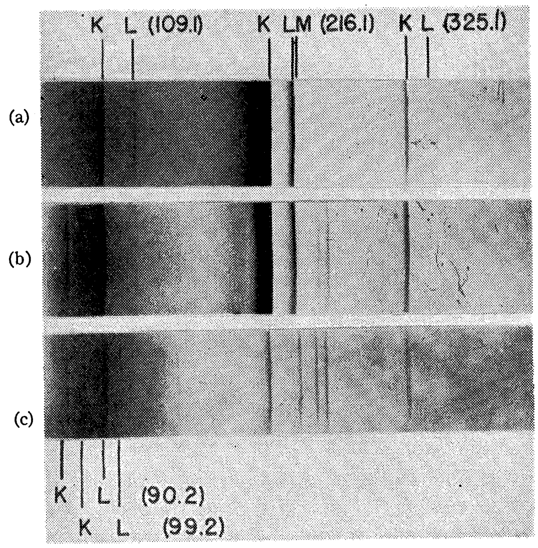


FIG. 2. Internal conversion spectra of Tc^{97} and Tc^{97m} for short- and long-period irradiations.

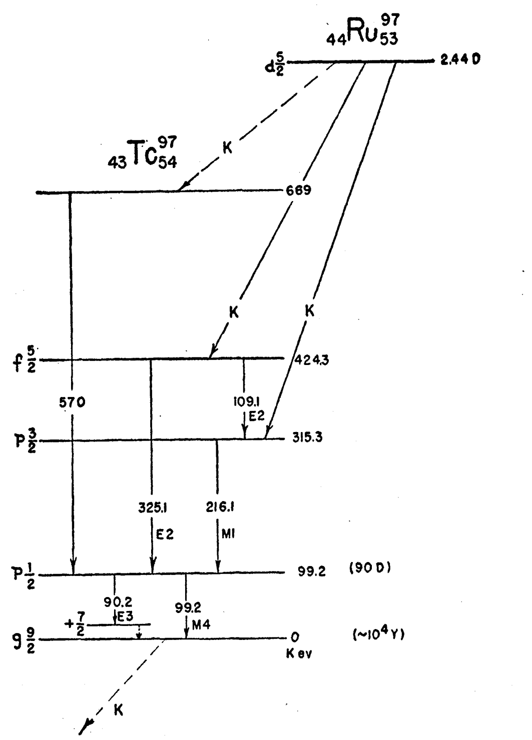


FIG. 3. Nuclear level scheme for Tc^{97}.

[4] Mihelich, Goldhaber, and Wilson, Phys. Rev. 83, 216 (1951).

greater than that of the K capture branch followed by the 109.1 transition. It is known from the coincidence data that the 216.1- and 325.1-kev radiations have half-lives shorter than about 10^{-6} sec, and the half-life of the 109.1 must be of the same order of magnitude as that of the 325.1. A comparison of the measured K/L ratios with the empirical curves[5] and of the information on conversion coefficients with the theoretical values[6] indicates that the 109.1-, 216.1-, and 325.1-kev transitions are, respectively, $E2$, $M1$, and $E2$. The 570-kev gamma probably follows another weak K capture branch, but its terminal level is uncertain. A nuclear level scheme for Tc^{97} consistent with the above information is shown in Fig. 3.

Note added in proof.—A consideration of the expected half-lives for the 9-, 90.2-, and 99.2-kev transitions indicates the possibility of interchanging the order of the 9- and 90.2-kev gammas. The 9-kev transition would then be interpreted as $E3$ and the 90.2-kev transition as of lower multipole order.

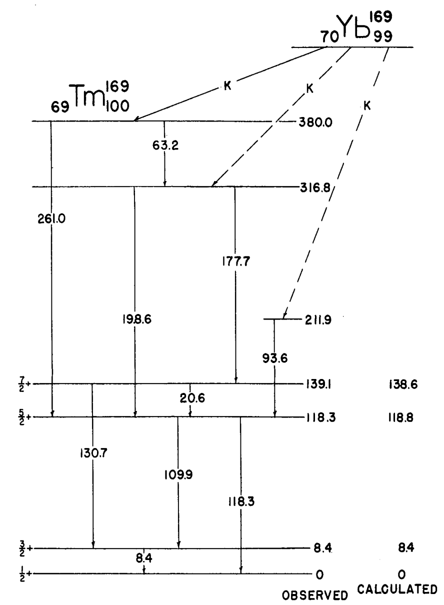
[5] M. Goldhaber and A. Sunyar, Phys. Rev. **83**, 906 (1951).
[6] Rose, Goertzel, and Perry, Oak Ridge National Laboratory Report ORNL-1023 (unpublished).

VI

NUCLEAR LEVELS IN Tm^{169}, Lu^{135}, AND Lu^{177} AS DERIVED FROM THE RADIOACTIVE ISOTOPES OF Yb

Reprinted from the Bulletin of the American Physical Society, Vol. 30, No. 7, 10 (1955)

Nuclear Levels in Tm^{169}, Lu^{175}, and Lu^{177} as Derived from the Radioactive Isotopes of Yb. J. M. Cork, M. K. Brice, D. W. Martin, L. C. Schmid, and R. G. Helmer, *University of Michigan.*—Using Yb of high purity (99.8%) irradiated in the maximum flux of the Argonne pile and studied by scintillation and magnetic photographic spectrometers, a re-evaluation of the energies of the radiations has been made. Several previously unreported gamma rays are found and nuclear level schemes for Tm^{169}, Lu^{175}, and Lu^{177} proposed. Several of the levels appear to be rotational states in the unified nuclear model. Yb^{169} decays with a half-life of 30.6 days by K capture, followed by eleven gamma rays in Tm^{169}. Rotational levels lie at 8.4, 118.3, and 139.1 kev. The gamma energies are 8.4, 20.6, 63.2, 93.6, 109.9, 118.3, 130.7, 177.7, 198.6, 261.0, and 308.3 kev. Yb^{175} decays with a half-life of 4.2 days by beta emission (474 kev max) followed by five gamma rays in Lu^{175}. Rotational levels exist at 114.1 and 251.9 kev. The gamma energies are 114.1, 137.8, 145.0, 282.9, and 397.0 kev. Yb^{177} decays with a half-life of 1.88 hours by beta emission followed by gamma transitions in Lu^{177}. In addition to any lower energy gamma rays, two high energy transitions are found at 1.080 and 1.228 Mev. The latter is a cross-over for the 1.080- and 0.148-Mev gammas which are in coincidence. The expected well-known daughter product Lu^{177}, if present at all, is too weak to be observed by the magnetic spectrometers, which suggests some possible error in the assignment of masses in the stable isotopes.



VII

DECAY OF Ca^{49} (8.4-min)

Reprinted from the Bulletin of the American Physical Society,
Vol. 30, No. 7, 9 (1955)

Decay of Ca^{49} (8.4-min).* DAVID W. MARTIN, S. BRADLEY BURSON, AND JAMES M. CORK, *Argonne National Laboratory.*—The beta and gamma radiations of radioactive Ca^{49} have been studied with the Argonne 256-channel coincidence scintillation spectrometer. Sources were prepared by irradiation in the Argonne reactor (CP 5) of samples enriched to about 12% in Ca^{48}. Gamma rays of 3.24 ± 0.05 and 4.30 ± 0.05 Mev were observed to decay with the 8.4 ± 0.1-minute period in the NaI (Tl) pulse-height distribution, in which a well collimated geometry was used. The 4.30-Mev gamma ray has an intensity of about 5% that of the 3.24-Mev transition. Calibration was based on the 4.45-Mev gamma ray of C^{12} excited by an (α,n) reaction in a shielded Po-Be source.[1] A beta ray with an end-point energy of 1.93 ± 0.10 Mev is found to be in coincidence with the 3.24-Mev gamma ray from a coincidence absorption curve. A softer beta ray in the neighborhood of 1 Mev is in coincidence with the 4.30-Mev gamma ray. The indicated decay energy of 5.1 ± 0.2 Mev is consistent with the beta decay systematics of this region of the nuclide chart.[2]

* Work performed under auspices of U. S. Atomic Energy Commission.
[1] R. J. Breen and M. R. Hertz, Phys. Rev. **98**, 599 (1955).
[2] K. Way and M. Wood, Phys. Rev. **94**, 119 (1954).