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INVESTIGATION OF NUCLEAR-ENERGY LEVELS

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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 1954.

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.

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Decay of $_{66}$Dy^{165m}(1.2 min) and $_{66}$Dy^{165}(2.3 hr)

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The activities induced by neutron capture in Dy^{164} have been studied with 180° photographic internal conversion electron spectrometers and a scintillation coincidence spectrometer. The metastable transition energy is 108.0±0.2 kev. Other gamma rays of approximately 160, 360, and 515 kev are associated with the 1.2-min activity and appear to follow beta decay from the metastable level. Gamma rays of 94.4±0.2, 279.4±0.8, 361.2±1.0, 634±3, 710±20, and 1020±30 kev follow the 2.3-hr beta decay from the ground state. Coincidences are observed between members of the pairs (279)-(710) and (361)-(634). The 94-kev gamma ray is coincident with a beta transition of about 1.2 Mev, while the other gamma radiations are coincident with a softer beta component (~0.3 Mev).

INTRODUCTION

IN 1935, Marsh and Sugden[1] and, independently, Hevesy and Levi[2] reported that a very strong beta activity was produced when Dy was exposed to neutrons from a Ra−Be source. They found the half-life to be about 2.5 hr. A recently reported value is 2.310 ±0.002 hr.[3] Several measurements of the beta energy using cloud chamber and absorption techniques have been made.[2,4–8] The values reported from these investigations range from 1.1 to 1.9 Mev. Two spectrometer measurements have listed the maximum beta energy as 1.18 Mev[9] and 1.24 Mev.[10] In addition to the 1.24-Mev beta ray, Slätis[10] has resolved two lower-energy components of 0.42 and 0.88 Mev. Meitner[6] reported gamma radiation with an average energy of about 0.6 Mev to be associated with this Dy activity. From a study of the internal conversion electron spectrum and the spectrum of electrons from secondary radiators, Slätis[10] concluded that gamma transitions of 0.91, 0.36, and 0.76 Mev were present. With the postulation of one additional unresolved beta component, he was able to propose a reasonable level scheme. Another measurement of the gamma-ray energies has been made by Miller and Curtiss,[11] who report energy values of 0.37 and 1.0 Mev. Clark[9] has set an upper limit of 1.1 Mev for the gamma energy and has also detected beta-gamma and gamma-gamma coincidences.

A short-lived Dy activity with a half-life of 1.25 min was first reported by Flammersfeld.[12] Electrons with an energy of approximately 130 kev were detected. These were interpreted as arising from internal conversion of an isomeric transition in Dy^{163}. Later work by Inghram *et al.*[13] has established that this, as well as the 2.3-hr activity, is associated with Dy^{165}. The cross sections for production of the 1.25-min and 2.3-hr activities were observed to be approximately equal, indicating that only the metastable state is formed directly in the capture process. Since growth of the 2.3-hr activity had not been observed,[12] it was suggested that a small percentage of the decay of the metastable state was by emission of a beta particle. In the present research some additional evidence for the existence of such a transition has been found.

The conversion electron spectrum of this activity has been investigated with spectrometers by Hole[14] and Caldwell.[15] The former noted that conversion was pre-

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[1] J. Marsh and S. Sugden, Nature **136**, 102 (1935).
[2] G. Hevesy and H. Levi, Nature **136**, 103 (1935).
[3] Sher, Kouts, and Downes, Phys. Rev. **87**, 523 (1952).
[4] R. Naidu and R. Siday, Proc. Phys. Soc. (London) **48**, 332 (1936).
[5] Gaerttner, Turin, and Crane, Phys. Rev. **49**, 793 (1936).
[6] L. Meitner, Arkiv Mat. Astron. Fysik **A27**, No. 17 (1940).
[7] S. Eklund, Arkiv Mat. Astron. Fysik **A28**, No. 3 (1941).
[8] A. F. Clark, Phys. Rev. **61**, 203, 242 (1942).
[9] B. Dzelepov and A. Konstantino, Compt. rend. acad. sci. (U.R.S.S.) **30**, 701 (1941).
[10] H. Slätis, Arkiv Mat. Astron. Fysik **A33**, No. 17 (1949).
[11] L. Miller and L. Curtiss, Phys. Rev. **70**, 983 (1946).
[12] A. Flammersfeld, Naturwiss. **32**, 68 (1944); Z. Naturforsch. **1**, 190 (1946).
[13] Inghram, Hayden, and Hess, Phys. Rev. **71**, 270 (1947); Inghram, Shaw, Hess, and Hayden, Phys. Rev. **72**, 515 (1947).
[14] N. Hole, Arkiv. Mat. Astron. Fysik **A36**, No. 2 (1948).
[15] R. Caldwell, Phys. Rev. **78**, 407 (1950).

dominantly in the *L* shell and found the transition energy to be 102 kev. The latter resolved five conversion lines and reported a value of 109.0 kev for the transition energy. By means of a scintillation spectrometer, Kahn[16] found a value of 102 kev. Caldwell also investigated the conversion electron spectrum of the 2.3-hr activity in the region below 300 kev. He observed several electron lines associated with conversion of an 87.8-kev gamma ray, and in addition, a single line at 219 kev. The latter has been interpreted[17] as the *K* line of a transition which could be fitted into the level scheme proposed by Slätis. As indicated in a preliminary report[18] of the present study, energy values of the transitions involved and the results of coincidence experiments are inconsistent with this interpretation.

An accurate measurement of the low-energy gamma ray has been made by Mihelich and Church.[19] They found the energy to be 95.1 kev and the ratio of conversion in the *K* and *L* shells to be 5.9.

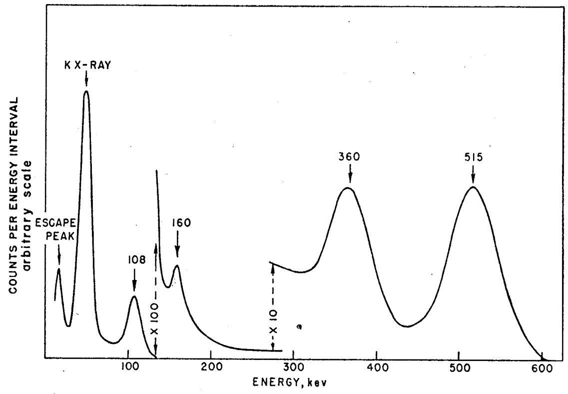

FIG. 1. Gamma-ray pulse-height distribution of $_{66}$Dy^{165m}(1.2 min).

EXPERIMENTAL PROCEDURE

The apparatus of the present investigation consists of several 180° photographic conversion electron spectrometers[20] and a scintillation coincidence spectrometer.[21]

Sources were normal Dy oxide irradiated in the Argonne heavy water—moderated reactor. Several samples of Dysprosium oxide were used. One was known to be spectrographically pure except for 0.4-percent holmium and 0.1-percent yttrium.

Eastman no-screen x-ray and NTB emulsions were used as detectors in the electron spectrometers. Film backings were used in survey work, but where density and accurate energy measurements were made, a glass plate backing was employed. Photodensitometer measurements of line intensities were practicable in the case of only two of the transitions. These measurements were made with a Leeds and Northrup recording photodensitometer. After the data were replotted on a linear scale and the background due to the beta distribution was subtracted, the area under a line profile was measured. This area, when corrected for variations due to the geometry of the spectrometer and sensitivity of the photographic emulsion, is taken as the relative intensity of the line. The geometry correction consists of simply multiplying each value by the corresponding radius of the electron path in the spectrometer. The emulsion sensitivity factor was determined according to the method described by Rutledge, Cork, and Burson.[20] No corrections are made for differential absorption of the electrons in the source.

TABLE I. Internal conversion electrons associated with the 1.2-min Dy activity.

Electron energy (kev)	Relative intensity	Interpretation	Energy sum (kev)	Transition energy (kev)	*K/L*
54.2	3	*K* (Dy)	108.0	108.0±0.2	0.15±0.05
99.4	10	L_2	108.0		
100.3	10	L_3	108.1		
106.3	5	M_2, M_3	108.1		
107.8	1.5	*N*	108.1		
461		*K* (Ho)	517	517±3	

RESULTS AND DISCUSSION

1.2 min

Internal conversion electrons associated with the 1.2-min metastable transition are easily detected. Five lines corresponding to a transition of 108.0 kev were observed (Table I). The energy is in fair agreement with the value 109 kev reported by Caldwell. A careful measurement of the separation of the two *L*-lines was made, and it was found that the energy difference is characteristic of conversion in the L_2 and L_3 sub-shells, as has been proposed by Mihelich.[22] It is interesting to

TABLE II. Internal conversion electrons associated with the 2.3-hr Dy activity.

Electron energy (kev)	Relative intensity	Interpretation	Energy sum (kev)	Transition energy (kev)	*K/L*
38.8	60	*K* (Ho)	94.4	94.4±0.2	7.7±2.0
85.0	7.8	L_1	94.4		
92.2	~1.5	*M*	94.3		
93.9		*N*	94.3		
223.8		*K* (Ho)	279.4	279.4±0.8	>5[a]
270.0		L_1	279.4		
305.8		*K* (Ho)	361.4	361.2±1.0	>5[a]
351.7		L_1	361.1		
578		*K* (Ho)	634	634±3	
~623		*L*	~632		

[a] Visual estimate.

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[16] J. Kahn, Oak Ridge National Laboratory Report ORNL 1089, 1951 (unpublished).

[17] M. Goldhaber and R. Hill, Revs. Modern Phys. **24**, 179 (1952).

[18] Jordan, Cork, and Burson, Phys. Rev. **91**, 497 (1953).

[19] J. Mihelich and E. Church, Phys. Rev. **85**, 690 (1952).

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

[21] S. Burson and W. Jordan, Phys. Rev. **91**, 498 (1953).

[22] J. Mihelich, Phys. Rev. **87**, 646 (1952).

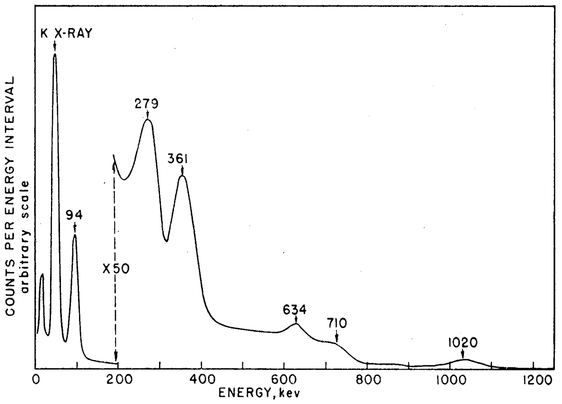

FIG. 2. Gamma-ray pulse-height distribution of $_{66}Dy^{165}$(2.3 hr).

note that the M conversion also appears to be in the M_2 and/or M_3 sub-shell.

The K/L conversion ratio is 0.15±0.05, a somewhat higher value than that obtained by Caldwell, but in good agreement with the Goldhaber and Sunyar[23] empirical relation of Z^2/E *versus* K/L for an electric octopole transition.

An investigation of the 1.2-min activity with the scintillation spectrometer revealed the presence of higher energy gamma radiations. Peaks in the pulse-height distribution corresponding to gamma rays of approximately 160, 360, and 515 kev are present in addition to the K x-ray, its associated escape peak, and the 108-kev peak (Fig. 1). All of these decay with the 1.2-min period. The ratio of the heights of the 360- and 515-kev peaks can be varied by placing lead absorbers between the source and the detector. Therefore, the 360-kev peak is not due entirely to excitation of the crystal by Compton electrons of the 515-kev gamma ray.

Coincidences between the 360- and 515-kev gamma rays were not observed. Pulses in the region of the 360-kev peak were, however, observed to be coincident with those of the 160-kev region. It is probable that the 160- and 360-kev transitions are in cascade and that the 515-kev one is the crossover.

It might be assumed that these gamma transitions follow the 108-kev metastable transition. However, these radiations appear to be coincident with a beta ray and not with the radiations associated with the metastable transition. Beta decay of the metastable state has not been detected previously, although the possibility of its existence has been suggested.[13] Additional evidence of this beta transition was observed with the photographic spectrometers. The background darkening of the emulsion, due to the continuous beta distribution, is markedly different on a plate exposed for short periods immediately after irradiation of the source, as compared with a plate with an equivalent exposure to the 2.3-hr activity after the 1.2-min activity had decayed. An additional weak conversion line was noted which may be associated with the short activity. The energy of the electrons is 461 kev. These are probably K electrons for the ~515-kev transition. If so, a better value for the energy of this transition is 517 kev, assuming the K binding energy of holmium is to be used.

By comparing the heights of the 108-kev and x-ray

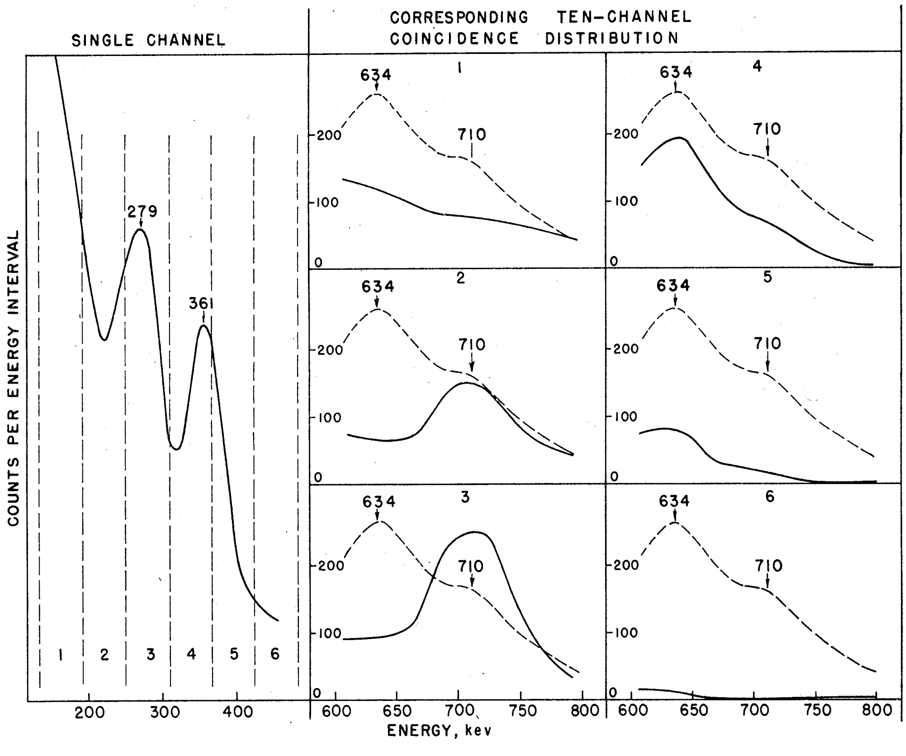

FIG. 3. Coincidence pulse-height distributions of $_{66}Dy^{165}$(2.3 hr). Six coincidence distributions corresponding to six window settings of the single-channel spectrometer are shown. For comparison, the normal spectrum is shown as a dashed curve in each case.

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[23] M. Goldhaber and A. Sunyar, Phys. Rev. 83, 906 (1951).

peaks (Fig. 1), a rough estimate of the K conversion coefficient of the 108-kev transition may be obtained. Neglecting any contribution to the x-ray intensity from conversion of the higher energy gamma rays, this quantity may be estimated to be about four. Since conversion of this transition is only about 10 percent in the K shell, the total conversion coefficient would be about forty.

2.3 hr

Internal conversion electrons associated with the 2.3-hr activity are listed in Table II. The observed conversion lines are interpreted as arising from four transitions of 94.4, 279, 361, and 634 kev. The measured energy of the 94.4-kev transition is in fair agreement with the results of Mihelich and Church. They report the energy to be 95.1 kev and the type of radiation as a mixture of $M1$ and $E2$. The present measurement of the K/L ratio is in good agreement with the value predicted for a pure $M1$ transition; however, the accuracy is too poor to rule out the possibility of the mixture. In the decay scheme of Goldhaber and Hill,[18] this transition is assumed to be in cascade with the 279-kev one, while the 361-kev is the crossover transition. This is not consistent with the present data. The discrepancy in the energy sum is well outside the limits of experimental error.

An investigation of this activity with the scintillation spectrometer showed the presence of peaks in the pulse-height distribution corresponding to the previously mentioned transitions, plus two others of approximately 710 and 1020 kev (Fig. 2). Coincidence studies showed that the 279- and 710-kev gamma rays form one cascade pair and the 361- and 634-kev gamma rays are another. These conclusions are based on the results of two complementary experiments.

In one experiment the ten-channel analyzer was adjusted to cover the region of the 634- and 710-kev peaks, while the single-channel spectrometer was varied in steps across the region of the 279- and 361-kev peaks. The resulting coincidence distributions are shown in Fig. 3. The peak in the coincidence distribution is at the 634-kev position when the single-channel side is accepting pulses from the 361-kev transition, and at the 710-kev position when the single channel is accepting pulses from the 279-kev gamma ray. The complementary experiment, in which the coincidence spectra in the region of the 279- and 361-kev peaks were observed as the single channel was scanned over the 634–710-kev region, yielded results in agreement with these.

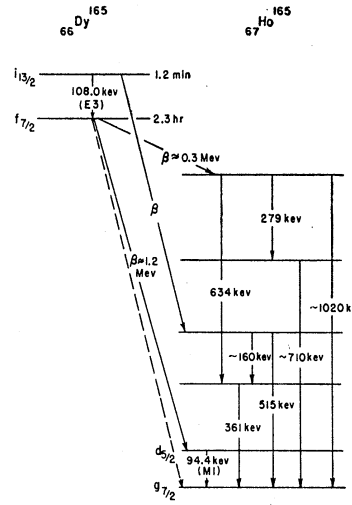

FIG. 4. Proposed decay scheme for $_{66}$Dy^{165m}(1.2 min) and $_{66}$Dy^{165}(2.3 hr). (The order of the 279–710-kev cascade is arbitrarily chosen.)

Coincidences between the other possible pairs of gamma rays were not detected.

The results of beta-gamma coincidence experiments indicate that the 94-kev transition is coincident with a beta ray of maximum energy approximately 1.2 Mev, while the other gamma radiations all appear to be coincident with a lower energy beta component of approximately 0.3 Mev.

The proposed nuclear energy level scheme shown in Fig. 4 is consistent with these data. It should be pointed out that the transition of about 360 kev associated with the 1.2-min activity has been assumed to be the same as the more accurately measured 361-kev transition associated with the 2.3-hr activity. Also, the order of the 279–710-kev cascade as shown in the figure is arbitrarily chosen.

The measured spin of the ground state of Ho^{165} is 7/2.[24] On the basis of shell structure, orbital assignments have been made[18] for the ground and first excited states of both Dy^{165} and Ho^{165}. The results of this investigation are in agreement with these assignments

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[24] H. Schüler and T. Schmidt, Naturwiss. **23**, 69 (1935).

II

THE GAMMA SPECTRA OF Cd^{117} AND In^{117}

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The Gamma Spectra of Cd^{117} and In^{117}. J. M. LeBlanc J. M. Cork,[*] and S. B. Burson, *Argonne National Laboratory.*—The gamma spectra of Cd^{117} and In^{117} have been studied with 180° photographic spectrometers and with a 10-channel coincidence scintillation spectrometer. Sources were obtained by irradiating enriched Cd^{116} in the Argonne heavy water reactor. Internal conversion electrons associated with 0.160-, 0.267-, 0.281-, and 0.312-Mev gamma rays were observed. In addition to these, transitions of energy 0.43, 0.55, 0.72, 0.84, 1.27, 1.55, and 2.00 Mev were detected with the scintillation spectrometer. The decay of each peak has been followed. Chemical separations of the In from the Cd were made and the spectra of each fraction studied with the scintillation spectrometer. Then 0.160-, 0.312-, 0.55-, and 0.72-Mev gamma rays are associated with the In fraction, and all decay with a 2.3-hour half-life. The remaining gamma rays are in the Cd fraction. The 0.312-Mev gamma ray is the most strongly converted, and, furthermore, is not in coincidence with beta-rays. It is interpreted as an isomeric transition in In^{117}. Results of beta-gamma and gamma-gamma coincidence measurements will be discussed.

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III

RADIATION FROM ANTIMONY 122

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Radiation from Antimony 122

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Neutron capture in enriched Sb^{121} yields radioactive Sb^{122} whose half-life is found to be 66.0±0.4 hr. In addition to the two previously observed gamma rays, present studies with scintillation and conversion electron spectrometers indicate the existence of six previously unreported gammas. The energies are 95, 553, 566, 616, 647, 694, 1100, 1200 kev with possibly something at 1.9 Mev. K/L intensity ratios for the conversion lines are observed only for the 553- and 566-kev gammas. The high-energy lines are observed only with the scintillation spectrometer. The beta spectrum is resolved into components with maximum energies at 2.00±0.03, 1.40±0.02, and 0.450 Mev, with possibly some other lower energy present.

Three gamma energies in Sb^{124} are evaluated by their conversion electrons as 603.6, 644, and 727 kev.

IN the early survey of radioactivities induced by slow neutron capture, Fermi *et al.* found[1] a beta-emitting product in antimony, whose half-life was 2.5 days and whose beta energy, as determined by absorption in aluminum, was about 1.6 Mev. Subsequent studies have shown[2] that this activity is undoubtedly in Sb^{122} being formed from Sb^{121} whose natural abundance is 57.2 percent. More recently several reports on the energies of the beta and the gamma radiations have appeared. These exhibit considerable variation in the value of the beta energies. In only one report is more than a single gamma ray mentioned. These results are summarized in Table I.

In the present investigation, antimony enriched in mass 121 up to about 99 percent was irradiated in the Argonne heavy-water pile. The gamma radiations were studied both with photographic magnetic and scintillation crystal spectrometers. The beta radiation has been analyzed by the large double-focusing magnetic spectrometer provided with a thin window counter. The half-life was determined from observation of the decay through several octaves by the use of an ionization electrometer.

BETA ENERGIES

The beta spectrum is found to be complex, consisting of at least three components. The composite Kurie plot is shown in curve *A*, Fig. 1. The curve shape at the upper limit suggests a unique first forbidden transition with ΔI equal to 2 and a change in parity. It is found that the high-energy part of the Kurie plot can be corrected to a straight line by means of the unique first-forbidden, tensor-type correction factor $C\sim(W_0-W)^2L_0+9L_1$, where the factors L_0 and L_1 are obtained from the tables of Rose *et al.*[3] A least squares fit to the corrected Kurie plot gives an upper energy limit of 2.00±0.03 Mev. The remainder after subtraction of this component is shown in Curve *B*. This residual curve is still complex, and its high-energy part does not exhibit the allowed shape. When the same correction factor as used above is applied, an upper energy limit of 1.40±0.02 Mev is found. Subtraction of this component gives a residual curve of maximum energy 450 kev (curve *C*). However, this energy value is influenced appreciably by the type of correction factor applied to curve *B*. The possibility of lower energy beta components is not excluded. The relative abundance of the three beta rays expressed in the order of decreasing energy is 36, 56, and 8 percent. The corresponding log *ft* values in the same order are 8.5, 7.7, and 6.7, respectively.

GAMMA ENERGIES

In the magnetic photographic spectrometers strong *K* and *L* electron lines appear with energies of 534.2 and 560.6 kev which, if in tellurium, yield a gamma ray at 566.0 kev. The *K* to *L* intensity ratio for the two lines is found to be 7.0±1.5. Weaker *K* and *L* lines are observed for a gamma ray of energy 553 kev, with a K/L value of approximately unity. Several additional single electron lines are found and interpreted as *K* lines in tellurium for gamma rays, following *K* capture in Sb^{122}. All observed lines died with the same half-life which was found to be 66.0±0.4 hr. The energies of these electron lines are 63.4, 584, 615, and 662 kev, yielding gamma rays with energies of 95.2, 616, 647, and 694 kev. The weakest line is that corresponding to

TABLE I. Previous data relative to Sb^{122}.

Author	Energy in Mev β_1	β_2	γ_1	γ_2
MC[a]	1.36	1.94		
RW[b]			0.57	
K[c]			0.568	
C[d]			0.568	
M[e]	1.19	1.77		
M[f]	1.46			
G[g]	3β's	(No values)	0.56	0.680

[a] L. Miller and L. Curtiss, Phys. Rev. **70**, 983 (1946).
[b] W. Rall and R. Wilkinson, Phys. Rev. **71**, 321 (1947).
[c] Kern, Zaffarano, and Mitchell, Phys. Rev. **73**, 1142 (1948).
[d] C. Cook and L. Langer, Phys. Rev. **73**, 1149 (1948).
[e] C. Mandeville and M. Scherb, Phys. Rev. **73**, 340 (1948).
[f] Macklin, Lidofsky, and Wu, Phys. Rev. **82**, 334 (1951).
[g] M. Glaubman and F. Metzger, Phys. Rev. **87**, 203 (1952).

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[1] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti, and Segrè, Proc. Roy. Soc. (London) A149, 522 (1935).

[2] Mitchell, Langer, and McDaniel, Phys. Rev. **57**, 1107 (1940).

[3] Rose, Perry, and Dismuke, Oak Ridge National Laboratory Report, No. 1459, 1953.

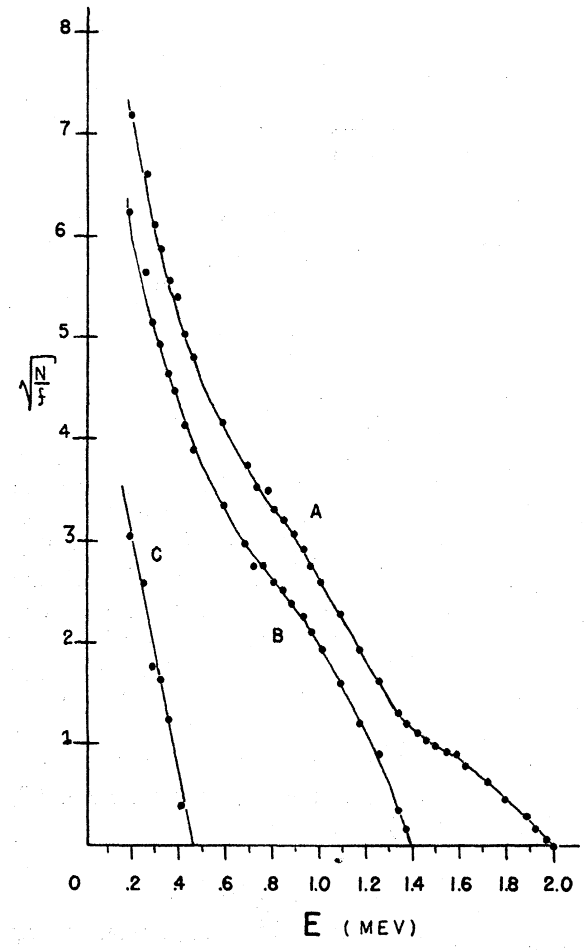

FIG. 1. Resolution of the beta radiation from Sb.^{122}

the gamma ray at 647 kev. A lead radiator giving photoelectrons showed *K* and *L* lines only for the strong 566-kev gamma ray.

To insure that none of the observed electron lines could be attributed to Sb^{124}, which has been previously intensively studied,[4] spectrometric exposures were made of a strongly irradiated source of Sb^{123}. The strongest electron line is found to have an energy of 571.8 kev. This is a *K* line and it is accompanied by an *L* line of about one-tenth its intensity, at 598.6 kev, so that the energy of the gamma ray is 603.6 kev. Weaker conversion electron lines are observed for gamma rays of energies 644 and 727 kev. Even the very strongest line at 571.8 kev is not observable on the spectrograms obtained with Sb^{122}, hence it seems quite certain that none of the gamma rays attributed to Sb^{122} could be due to Sb^{124}.

Studies have also been made of the activity with a scintillation crystal spectrometer. Due to the increased sensitivity of this method, some slight response is obtained for radiation due to Sb^{124}, particularly at high energies. Peaks are obtained for gamma rays at 1.09 and 1.68 Mev with possibly something at 1.2 Mev and also at a higher energy such as 1.9 Mev, as shown by the singles curve *A*, in Fig. 2. After a decay of 7 days this trace has dropped to give the relative intensities shown in curve *B*, thus indicating that the 1.68-Mev gamma ray is in Sb^{124} with its longer half-life, while the 1.10-Mev gamma and possibly the 1.2- and 1.9-Mev transitions are in Sb^{122}. In the low-energy region, peaks are observed only for the gamma rays of energy 694, 566, and 27 kev. The last is due undoubtedly to the *K* x-rays of tellurium following *K* capture in antimony. The energy is evaluated by comparison with the known peaks due to Cs^{137} and Co^{60}. For the very strong 566-kev radiation both Compton electron and escape peaks are observed as shown.

COINCIDENCE STUDIES

By placing the radioactive source between two scintillation crystals each with its own output circuit, coincidence events could be observed. For gamma-gamma coincidences both crystals were made of NaI, thallium activated. For beta radiations a crystal of anthracene was employed. The window of one pulse-height analyzer could be adjusted to respond to gamma rays lying between definite energy limits and the other instrument could be swept through all of the gamma peaks in turn. In beta-ray studies the anthracene with its very thin window actuated one of the recording circuits. By interposing successive layers of aluminum between source and crystal the counting rate was reduced so as to obtain a Feather curve. Either the thickness required to reduce the intensity to half-value, or the thickness required to reduce to the gamma background, may be used empirically to give the beta upper energy limit.

In Fig. 2 is also shown a coincidence curve *C*, when one channel is set to respond only to the 566-kev radiation and the other channel is varied to respond to successive gamma rays. The 566-kev radiation is thus seen to be in sequence with the 694-kev gamma. No evidence could be obtained for the gamma-gamma coincidences except for the tellurium x-ray at 27 kev.

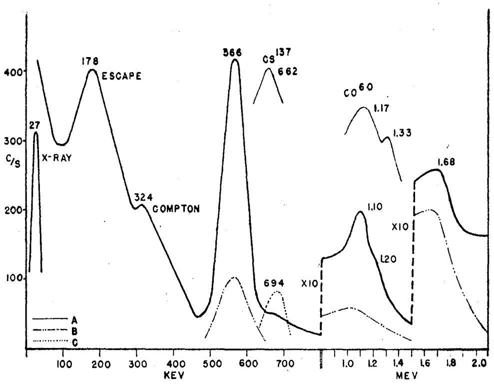

FIG. 2. Energy distribution with the scintillation spectrometer.

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[4] Langer, Lazar, and Moffat, Phys. Rev. 91, 338 (1953); Tomlinson, Ridgeway, and Gohalakrishnan, Phys. Rev. 91, 484 (1953).

The beta activity as a function of the thickness of aluminum is shown in curve *A*, Fig. 3. The thickness required to reduce the activity to that of the gamma background cannot be sharply determined but it is approximately 0.9 g/cm^2 corresponding to an energy of about 1.9 Mev. By recording only coincidences between beta response and the 566-kev gamma ray as the absorber is varied in thickness, curve *B* is obtained. The cut-off thickness is now 0.6 g/cm^2 indicating an energy of 1.4 Mev. This indicates that the 566-kev gamma transition follows in sequence the 1.4-Mev beta decay. Attempts to observe other beta-gamma coincidences were not successful.

The ground level of the even-even $_{52}Te^{122}$ nucleus is undoubtedly a state of zero spin and even parity. If the uniquely forbidden 2.00-Mev beta transition goes directly to the ground state, then the 66-hour $_{51}Sb^{122}$ level is identified as having a spin of two and odd parity. There exists also in Sb^{122} a 3.5-minute isomeric state which has been reported[5] to decay by a 69-kev gamma to the more stable level. The Z^2/W value for the 566-kev radiation is 4.8. In this region a K/L ratio of approximately 7 cannot uniquely determine the type of radiation, and on this basis alone it might be an $E2$ or any type of magnetic transition. The observation of coincidences with beta rays requires a short lifetime which would exclude all magnetic transitions except $M1$, and possibly $M2$. For even-even nuclei the first excited state is usually a level with spin two and even parity, which allows an $E2$ transition to the ground state. The nature of none of the other gamma transitions can be resolved. The low K/L ratio for the 553-kev gamma ray suggests a high-order multipolarity for the transition, such as $E4$ or $M4$. A long lifetime should then be expected which may account for the absence of additional coincidences.

It is possible to arrange a level scheme that will accommodate most of the observed data. Cross-over transitions can be identified from the fact that certain gamma energies have values approximating the sums of others. For example, 566 plus 553, 566 plus 694, and 95 plus 553 will yield 1119, 1260, and 648, respectively, all of which are observed. No trace of positrons could be observed but there might conceivably be *K* capture leading to Sn^{122}. In this event some of the gamma rays might occur in tin. Level schemes that appear reasonable seem to require an additional low-energy beta ray which is beyond the resolution of the present work.

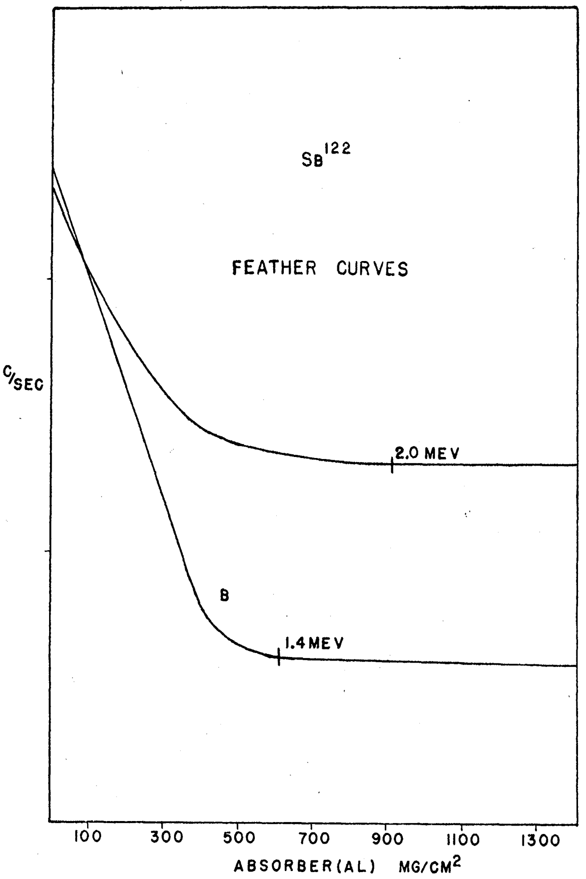

FIG. 3. Absorption of beta radiation observed with scintillation spectrometer.

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

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[5] E. derMateosian and M. Goldhaber, Phys. Rev. **82**, 115 (1951); J. H. Kahn, Oak Ridge National Laboratory Report, No. 1089, November, 1951.

IV

DECAY OF V^{52}

Reprinted from The Physical Review, Vol. 93, No. 5, 1124–1125, March 1, 1954
Printed in U. S. A.

Decay of V^{52}

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(Received January 14, 1954)

THE irradiation of normal V with thermal neutrons has been reported to produce three activities[1] which have been assigned to V^{52}. These activities were found to decay with half-lives of 2.6 min, 3.75 min, and 16 hr. Recent work has been reported[2] on the 16-hr activity and an energy level scheme proposed which includes all three activities.

The present study of V^{52} was made using 180° magnetic photographic spectrometers and a 10-channel coincidence scintillation spectrometer. Sources were obtained by neutron irradiation of V_2O_5 in the Argonne heavy water reactor.

Irradiations of about 5 minutes produce a strong 3.75-min activity in V. The conversion electron spectrum of such samples was examined in the region of 10 kev to 2 Mev, and no electron lines were detected. The scintillation spectrometer was used to study the unconverted photons, and the resulting spectrum is shown in Fig. 1. It is clear that there is only one gamma ray present to any appreciable extent in this activity. Its energy is 1.44 ± 0.02 Mev, and its half-life is 3.75 min. The β rays were studied by absorption in Al, and it was found that a β ray whose maximum energy is about 2.6 Mev is in coincidence with the 1.44-Mev gamma ray. The coincidence Al absorption curve did not differ from the singles absorption curve, so that it is concluded that most, if not all, of the beta rays feed the 1.44-Mev level in Cr^{52}.

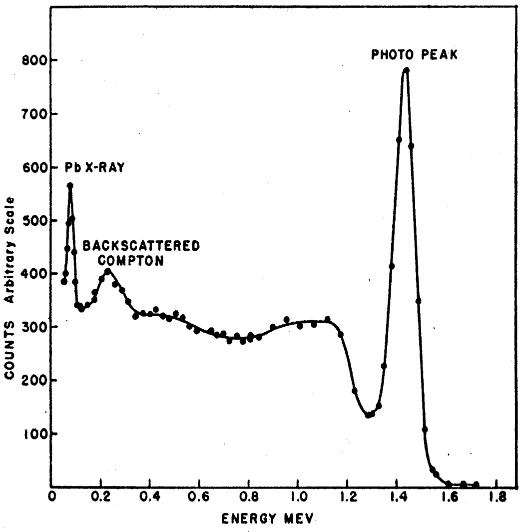

FIG. 1. Gamma-ray pulse-height distribution resulting from V^{52} (3.7 min).

An attempt was made to detect the 2.6-min activity reported by Renard. Sources were irradiated for periods of 1, 3, and 10 minutes and their decay followed with an ionization chamber and a vibrating reed electrometer. The decay curves were all simple, with a half-life of about 3.7 min. Other investigators[3] also find no evidence for the metastable state in V^{52} reported by Renard. The assignment of a 2.6-min activity to V is thus considered to be doubtful.

A weak activity with a half-life of about 15 hr was found in V samples irradiated for about 15 hr. The scintillation spectrum of this activity, however, corresponds to the spectrum obtained from the 15-hr Na^{24}. A spectroscopic analysis of the V_2O_5 established that Na was an impurity with 0.05 percent abundance. In order to determine if any of the activity was due to V, the Na was chemically separated from the V after irradiation. Both the Na and the V fractions were then counted with the scintillation spectrometer. It was found that the activity of the Na fraction was more than 100 times that of the V fraction, and that the V fraction was only two times the background.

The results of this study indicate that V^{52} decays with a 3.75-min half-life by the emission of a single beta ray of energy 2.6 Mev followed by a gamma ray of energy 1.44 Mev. Neither the 2.6-min nor the 16-hr activity previously reported in V^{52} was found.

The authors wish to thank P. R. Fields, R. F. Barnes, and J. K. Brody of the Argonne National Laboratory for kindly making the chemical separation and spectroscopic analysis.

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* University of Michigan, Ann Arbor, Michigan.

[1] E. Amaldi *et al.*, Proc. Roy. Soc. (London) **A149**, 522 (1935); G. A. Renard, Ann. phys. **5**, 385 (1950); Cork, Keller, and Stoddard, Phys. Rev. **76**, 575 (1949); L. A. Turner, Phys. Rev. **58**, 679 (1940).

[2] T. Wiedling, Phys. Rev. **91**, 767 (1953).

[3] J. E. Schwager and L. A. Cox, Phys. Rev. **92**, 102 (1953); G. A. Bartholomew and B. B. Kinsey, Phys. Rev. **89**, 386 (1953).

V

NEUTRON CAPTURE IN THE SEPARATED ISOTOPES OF PLATINUM

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Neutron Capture in the Separated Isotopes of Platinum*

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(Received Februrary 23, 1954)

Using the separated isotopes of platinum, irradiated in the pile, the energies of the gamma rays for the activities of Pt^{191}, Pt^{193}, and Pt^{195} have been evaluated. For Pt^{191} fifteen gamma rays are found which fit well a simple level scheme. Pt^{193} emits isomerically a gamma ray followed by K capture to iridium, with the possible emission of a high-energy gamma. Pt^{195} emits a highly converted gamma ray followed by two others in rapid succession decaying to the stable isotope. The half-lives of the three activities are found to be 2.90, 3.35, and 6 days, respectively.

THE irradiation of normal platinum with low-energy neutrons yields five radioactive isotopes in platinum as well as one activity in gold. The correct assignment of each activity to its proper isotopic mass has been a difficult problem. For example, there has been no positive criterion for distinguishing between the activities at masses 191 and 193. By bombarding iridium with either protons or deuterons both can be made. Fast neutron bombardments have been of value, but since four of the activities have half-lives differing not greatly from 3 days, the difficulty is apparent. Only by the separation or enrichment of the less abundant isotopes of platinum can the assignments be made with confidence. The Oak Ridge National Laboratory has recently made available these separated isotopes. Specimens enriched in each of the masses 190, 192, and 194 have been irradiated in the heavy-water pile at the Argonne National Laboratory, and quickly transported for studies in scintillation crystal and magnetic photographic spectrometers.

TABLE I. Summary of electron energies for Pt^{191}.

Electron energy kev	Interpretation	Energy sum kev	Electron energy kev	Interpretation	Energy sum kev
20.5	K	96.2	164.9	L_1	178.2
49.5	Auger KL_1L_1		168.8	M	172.0
51.0	Auger KL_1L_3		175.0	N	178.2
53.6	K	129.6	192.9	K	268.6
60.0	L_1	73.7	206.0	L_1	219.4
	or Auger KL_1M_1		216.4	M	219.5
62.2	L_3	73.7	255.0	L_1	268.3
	or Auger KL_3M_1		274.8	K	350.9
69.0	L_1	82.6	284.0	K	360.0
69.8	L_2	82.6	333.3	K	409.2
71.4	L_3	82.7	338.0	L	351.0
79.8	M_1	82.7	346.0	L	359.5
81.8	N	82.7	356.8	M	359.9
83.4	$L_{1,2}$	96.4	380.0	K	456.0
85.0	L_3	96.4	396.0	L	409.4
			442.6	L	456.0
93.3	M	96.3	463.2	K	539.3
96.1	K	172.2	476.0	K	550
102.7	K	178.6	525.5	L	539.0
116.0	L_1	129.4	535.7	M	539.0
118.3	L_3	129.8	547.5	K	623.6
144.2	K	220.1	609	L	622.4
159.0	L_1	172.5			

PLATINUM 191

The first assignment[1] of a 3-day activity to Pt^{191}, from the products formed in platinum by the bombardment of iridium with deuterons, has proved to be a fortunate choice. Subsequent studies[2,3] have shown this activity to yield many gamma rays, following K capture, as shown in columns 1 and 2 in Table II. The gamma transitions are in iridium, following K capture in platinum. In the present investigation most of the previously reported gamma rays are found, with only slight modification in their energies. However, no evidence can be found for the existence of gamma rays with energies of 42, 62, and 125 kev in Pt^{191}. In addition there appear to be gamma rays of energy 73.7 and 550 kev, which were not previously observed. The half-life is found to be 2.90 ± 0.05 days.

The energies of the conversion electrons taken with various magnetic fields are summarized in columns 1 and 4 in Table I. The interpretation of each line and the energy sums are given in following columns. By comparing the lower-energy lines in Pt^{191} with the similar pattern obtained with Pt^{193} it is possible to identify those electron lines that are due to Auger groups. Thus, the gamma ray reported by Hill *et al.*[2] as 62 kev is probably of this origin. No evidence whatever appeared to support the existence of a gamma ray at 42 kev, although its L and M lines should have been easily observed if present. The gamma reported at 125 kev is probably based upon the assumption that the electron group at 49.5 kev is a K line. It is believed, however, that the better interpretation of this line is that it is of Auger origin corresponding to the very strong $K-L_1-L_1$ electron group. It thus appears that there are, in all, fifteen gamma rays, as shown in column 3, Table II.

The scintillation crystal spectrometer could of course not resolve these gamma energies when they are close together in value. It could, however, show broad peaks and yield valuable coincidence data. For example, the 172-kev gamma ray appears to be in sequence with radiation at 82, 96, and 178 kev but

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* This research was supported jointly by the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] G. Wilkinson, Phys. Rev. **73**, 252 (1948).

[2] Swann, Portnoy, and Hill, Phys. Rev. **90**, 257 (1953).

[3] Tomlinson, Naumann, and Mihelich, Bull. Am. Phys. Soc. **29**, No. 1, 57 (1954).

not with 350-kev or higher-energy peaks. By observing that summations of certain of the reported energies yield other observed energies, it is readily possible to construct a very plausible array of levels as shown in Fig. 1, that will satisfy almost perfectly all fifteen gamma energies. Twelve of the transitions are definitely accommodated by only six levels. The three rather weak gamma rays at 73 550 and 623 kev seem to form a group whose ground state may be any of the other levels. If they are correctly placed in Fig. 1, then there must be three K-capture paths from the excited platinum level. This specimen was not entirely free from iridium as an impurity so that weak lines for the well-known Ir^{192} spectrum were also obtained.

The ground state of Ir^{191} with its 77 protons and 114 neutrons has been measured to be a $d_{\frac{3}{2}}$ level. The first excited level to be expected from shell theory would be an $s_{\frac{1}{2}}$ state. If the proposed level scheme is correct, then the 82.6-kev transition should be characterized as $M1$. Its K electron group is too low in energy to be observed in the spectrometers but the L_1, L_2, and L_3 lines are well resolved and visually appear to be of almost equal intensity. The microphotometer could not well separate the L_1 and L_2 peaks but showed for the $(L_1+L_2)/L_3$ ratio a value of 1.8. This is compatible with a mixture of $M1+E2$ transitions as found[4] in a very similar case in gold 195 (61 kev) by Mihelich *et al.*

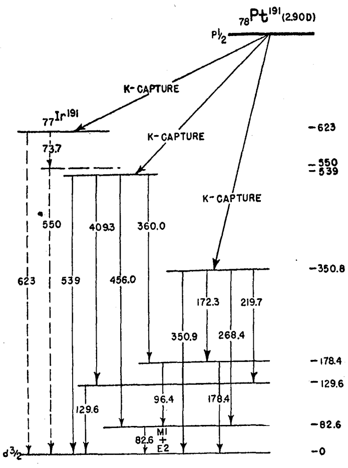

FIG. 1. Nuclear energy levels in Ir^{191} following K capture in Pt^{191}.

The K/L_1 intensity ratios for several of the remaining gamma rays are estimated visually as follows: 96.4 kev (~2), 129.6 kev (~3), 172.3 kev (~5), 350.8 kev (~9), 360 kev (~7), 409 kev (>10), 456 kev (~9), and 539 kev (~7). The L_3/L_1 ratio for the 129.6-kev gamma is ~0.12, which combined with its K/L ratio and the low L_2 intensity indicates that it is probably an $M1$ transition. It is possible to make assignments of the multipole order of most of these transitions, which make possible consistent spin assignments to the levels in Fig. 1.

TABLE II. Comparison of gamma energies (kev) in Pt^{191}.

	Observer	
Swann *et al.*[a]	Tomlinson *et al.*[b]	Present
...	42	...
62	...	...
...	...	73.7
82	82	82.6
94	96	96.4
125	125	...
129	...	129.6
171	172	172.3
178	179	178.4
...	220	219.7
267	268	268.4
350	350	350.9
359	360	360.0
408	409	409.3
455	456	456
537	540	539
...	...	550
...	620	623

[a] See reference 2.
[b] See reference 3.

PLATINUM 193

By bombarding platinum with fast neutrons a radioactivity with half-life 3.4 days was observed[5] by Hole. He noted electron conversion lines for a gamma ray of energy 126 kev and believed the activity to be isomeric in one of the stable isotopes of platinum. A similar bombardment by fast neutrons, as carried out by Wilkinson[1] was found to yield a radioactive product whose half-life was 4.33 days. The gamma rays emitted were reported to have energies of 0.17 and 1.70 Mev and the responsible isotope was believed to be Ir^{193} following K capture in Pt^{193}. More recent studies[2] by Hill *et al.* have led to the conclusion that Pt^{193} decays by an isomeric gamma transition of 134.9 kev, with an assumed half-life of 4.5 days.

In the present investigation, the enriched Pt^{192} after irradiation showed a strong low-energy gamma ray which is highly converted. The energies of the K, L_1, L_3, M, and N electron lines are 57.1, 121.6, 124.0, 132.3, and 134.8 kev, respectively, indicating a gamma energy of 135.5 kev. The intensity ratio for the K/L_1 lines is 0.25 ± 0.1, and for the L_3/L_1 ratio, a value of 1.5 ± 0.5 is found. This supports the interpretation[2] of the $M4$ nature of this radiation. Moreover the half-life appears to be not 4.5 days but 3.35 ± 0.1 days. This is in better agreement with the lifetime expected for radiation of this nature as computed from the formula[6] of Moszkowski.

The scintillation crystal spectrometer showed a high-energy gamma ray in this source in the neighborhood of 1.6 Mev. This peak seemed to decay at the same rate as that for the 135-kev gamma. Because of the high sensitivity of the crystal detector and the possibility of impurities, it cannot be said with certainty that this gamma ray is in Pt^{193}. The ground state

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[4] Gillon, Gopalakrishnan, De-Shalit, and Mihelich, Phys. Rev. **93**, 124 (1954).

[5] N. Hole, Arkiv. Mat. Astron. Fysik **36A**, No. 9 29 (1948).

[6] S. A. Moszkowski, Phys. Rev. **89**, 474 (1953).

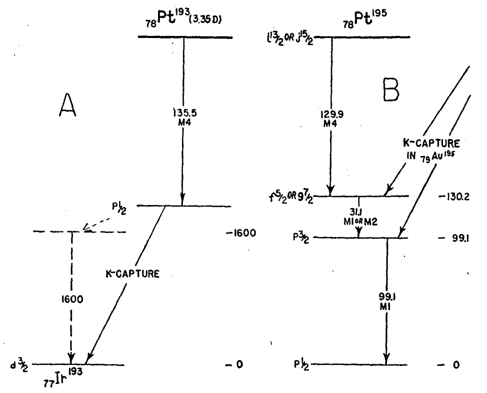

FIG. 2. A: Transitions in Pt^{193}; B: level scheme for Pt^{195}.

of Ir^{193} is a $d_{\frac{3}{2}}$ level, so that the K capture to the ground state from a $p_{\frac{1}{2}}$ level in Pt^{193} would be only first forbidden. A number of gamma rays have been found[7] to exist in Ir^{193} following beta emission from Os^{193}. None of these are observed in the present study of Pt^{193}, indicating that the main K-capture transition is to the ground state of Ir^{193}, as shown in Fig. 2(A).

PLATINUM 195

Following the irradiation of normal platinum with neutrons, a group of electron lines was observed,[8] which with the work functions of platinum gave two gamma rays with energies of 99.1 and 129.8 kev. These energies were somewhat similar to values reported,[9] in the decay of Au^{195} (185 day), and it was thus proposed that a metastable level probably exists in Pt^{195} with a half-life of the order of 4 days. To verify this speculation, in the present investigation platinum enriched in mass 194 was irradiated in the pile. This specimen showed clearly the strong conversion electron lines for three gamma rays in platinum, whose energies are 31.1, 99.1, and 129.9 kev. The electron energies with their approximate intensities are shown in Table III.

In a later investigation Huber *et al.* reported[10] on the gamma energies from both Pt^{195} and Au^{195}. The energies for the former were given as 29, 97, and 129 kev and for the latter 29, 97, and 126 kev. It was concluded that the 126-kev gamma ray was a crossover for the 29- and 97-kev transitions in sequence. The 129-kev radiation was assumed to precede the others, having its origin in a metastable state of Pt^{195} of half-life 3.8 days. Each of these energies for Pt^{195} appears to be too low by about 2 kev.

TABLE III. Electron energies associated with Pt^{195}.

Electron energy (kev)	Intensity	Interpretation	Energy sum (kev)
17.1	32	L_1	31.0
20.8	23	K	99.2
27.8	5	M_1	31.1
51.6	10	K	130.0
85.3	13	L_1	99.1
87.6	1	L_3	99.1
95.7	5	M	99.0
116.0	50	L_1	129.9
118.4	85	L_3	129.9

From a consideration of our energies alone, namely, 31.1 plus 99.1 being so close in value to 129.9, one would confidently but mistakenly assert that the latter is a crossover for the other gammas. By comparing our photographic records for Pt^{195} with similar plates obtained[4] by Mihelich *et al.* for Au^{195} the arrangement can be quite definitely established. His energy values for the 31.1- and 99.1-kev gammas agree well with ours but he finds no gamma energy corresponding to their sum. Moreover, the relative intensity of the electron lines is quite different. In Pt^{195} we find that the L_1 (31-kev) line is considerably stronger than the K (99-kev) line, whereas he finds for Au^{195} that the former is weaker. This indicates that the 31-kev transition precedes the 99-kev emission, so that two K-capture paths exist in the Au^{195} as previously suggested[10] and shown in Fig. 2B. If our observed 130-kev gamma is a cross-over transition it would have been observed by Mihelich, since it is highly converted. It then seems certain that this line is in platinum and does not appear in the gold decay. The K/L_1 and L_3/L_1 intensity ratios for the 130-kev gamma are about 0.2 and 1.7, respectively. From established[11] empirical relations it would seem to be an $M4$ transition. The expected lifetime of the state would be compatible with the observed half-life of the activity, which is found to be about 6 days.

The 31- and 99-kev gamma rays are also highly converted. In both cases L_1 is very strong compared to L_2 or L_3, thus suggesting $M1$ or possibly $M2$ transitions. The K/L_1 ratio (~ 2) for the 99-kev gamma would favor an $M2$ assignment. The half-life of an $M2$ state for this radiation ($Z^2/W = 61.5$) would be expected to be about 6 microseconds. Since coincidences were observed between the 31- and 99-kev radiations, no such delay exists. Moreover, the very small L_3/L_1 intensity ratio (<0.1) favors strongly an $M1$ assignment.

With the scintillation crystal spectrometer peaks were observed for the 30-, 60 (x-ray)-, 100-, and 130-kev gamma rays. Coincidences are observed between (30, 100), (30, x-ray), (x-ray, x-ray). No coincidences could be noted between the 130-kev radiation and either of the other gamma rays. This could be due to the very high conversion coefficient[12]

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[7] Cork, LeBlanc, Nester, Martin, and Brice, Phys. Rev. **90**, 444 (1953).

[8] Cork, Le Blanc, Stumpf, and Nester, Phys. Rev. **86**, 415 (1952).

[9] Steffen, Huber, and Humbel, Helv. Phys. Acta **22**, 167 (1949).

[10] De-Shalit, Huber, and Schneider, Helv. Phys. Acta. **25**, 279 (1952).

[11] M. Goldhaber and A. Sunyar, Phys. Rev. **85**, 733 (1952): and J. Mihelich, Phys. Rev. **87**, 646 (1952).

[12] Rose, Goertzel, and Perry, Oak Ridge National Laboratory Report No. 1023, 1951 (unpublished).

($\sim$800) for this radiation or to the possibility that the 30-kev gamma is an $M2$ transition, so that the delay would make coincidences unobservable. The very low value of the L_3/L_1 intensity ratio for this radiation favors but does not assure that it is an $M1$ transition.

The half-life of this radiation is considerably longer than the previously published values, which were undoubtedly influenced by the presence of other shorter-lived radioactivities. From a comparison of the intensities of the electron lines on a sequence of plates taken with known exposure times, the half-life appears to be approximately 6 days.

VI

THE ACTIVITIES OF Zn^{71}

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Vol. 94, No. 5, 1436, June 1, 1954

The Activities of Zn^{71}. J. M. LEBLANC, J. M. CORK,* AND S. B. BURSON, *Argonne National Laboratory.*—The activities of Zn^{71} have been investigated with a 10-channel coincidence scintillation spectrometer. Sources were obtained by the irradiation of enriched Zn^{70} and normal Zn in the Argonne heavy-water reactor. Two activities were found to be present in Zn^{71}; these decay with half-lives of 2.2 min and 3 hr. The 3-hr state of Zn^{71} decays by the emission of beta rays followed by three gamma rays of energies 0.38, 0.49, and 0.61 Mev. The attenuation by Al of the beta rays in coincidence with each of the gamma rays was measured and found to be the same in each case and to represent a beta ray of maximum energy of 1.5±0.1 Mev. In addition each gamma ray is found to be in coincidence with the remaining two gamma rays. It is therefore concluded that the three gamma rays found in this activity are in cascade and the upper level is fed by a beta ray of 1.5 Mev. The 2.2-min state of Zn^{71} is found to decay by the emission of a 2.4±0.2-Mev beta ray which is followed by a 0.51-Mev gamma ray. Additional weak gamma rays of energies 0.12, 0.90, and 1.05 Mev were also found to be associated with this activity and to follow beta emission. Gamma-gamma coincidence studies indicate that the 0.51 and 0.12-Mev gamma rays are not in coincidence.

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VII

THE DECAY OF Pt^{199}

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Vol. 95, No. 2, 627, July 15, 1954

The Decay of Pt^{199}. J. M. LeBlanc, J. M. Cork,[*] and S. B. Burson, *Argonne National Laboratory.*—The beta and gamma rays associated with the decay of 30-min Pt^{199} have been studied using 180° photographic spectrometers and a 10-channel coincidence scintillation spectrometer. The beta rays were studied by measuring their attenuation in Al. Sources were obtained by irradiating normal PtO in the Argonne heavy water reactor. Nine gamma rays of energies 0.07, 0.197, 0.246, 0.316, $\sim$0.48, 0.54, 0.71, 0.78, and 0.96 were found to decay with a 30-min half-life and are therefore assigned to this activity. Conversion electron lines were obtained for the 0.197, 0.246, and 0.316-Mev gamma rays. The results of beta-gamma coincidence measurements indicate that the 0.197, 0.246, 0.316, and 0.54-Mev gamma-rays are in coincidence with beta rays having an end point energy of about 1.2. Gamma-gamma coincidences will be discussed.

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VIII

ENERGIES OF THE RADIATIONS FROM Ce^{144} AND Pr^{144}

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Energies of the Radiations from Ce^{144} and Pr^{144}†

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(Received August 16, 1954)

With scintillation and magnetic photographic spectrometers the energies of the gamma rays from Ce^{144} have been re-evaluated. Several previously reported gamma rays are believed not to exist, while certain others not reported are found to occur. Gamma energies of 33.4, 40.8, 53.2, 59.0, 79.9, 95.0, 133.5, and 145.2 kev are found. Coincidence measurements together with a consideration of energy relationships indicate a reasonable level scheme for the Pr^{144} nucleus. The energies of the three high-energy gamma rays in Nd^{144} following beta decay of Pr^{144} are 0.688, 1.49, and 2.18 Mev. Some relative intensity measurements are made of the conversion electron lines, leading to a prediction of the multipolarities for three of the gamma transitions. The beta spectrum from Ce^{144} resolves into components with upper energies of 327, 258, and 160 kev. The beta radiation from Pr^{144} has an upper energy limit at 3.12 Mev with a lower energy component whose maximum energy is 0.92 Mev.

A LONG-LIVED radioactive cerium isotope was first isolated from fission products by Hahn and Strassman[1] in 1940. Many subsequent investigations[2] assigned the activity to the isotope of mass 144 and fixed the half-life at about 300 days. No evidence for the existence of gamma rays was presented in the earlier reports. When stronger sources became available from the Oak Ridge National Laboratory it was found that several gamma rays accompany the beta decay of Ce^{144} to Pr^{144}. The Pr^{144} decays mainly by beta emission (~3 Mev) with a half-life of 17 minutes to the ground state of Nd^{144}. Weak high-energy gamma radiation accompanies this disintegration through a competing process with a very low percentage.

In the present investigation a fission source of high specific activity was used with both scintillation and magnetic photographic spectrometers to check the previously reported results. The energies of the observed electron conversion lines are presented in Table I, along with their interpretations. By carefully considering each electron line in relation to its neighboring lines, it now appears reasonably certain that in several cases the gamma energies are not correct as previously published. In Table II, the results of previous investigations are shown together with the conclusions of the present investigation.

TABLE I. Electron energies from Ce^{144}.

Electron energy	Interpretation	Energy sum	Electron energy	Interpretation	Energy sum
26.6 kev	L_1 (59)	33.4 kev	57.6 kev	M	59.1 kev
28.5	Auger KL_1L_1		73.1	L_1	79.9
31.7	M	33.4	73.9	L_3	79.9
34.0	L_1	40.8	78.4	M	79.9
38.1	K	80.1	88.2	L	95.0
39.3	M	40.8	91.6	K	133.6
46.4	L_1	53.2	103.2	K	145.2
52.2	M	53.7	126.7	L	133.5
or	L_1	59.0	131.9	M	133.4
53.0	L_3	59.0	138.6	L	145.4
or	K	95.0	143.7	M	145.3

It seems quite definite that gamma rays of energy 46.8, 60.3, 100, and 231 kev do not exist and that others at 59.0 and 145.2 do occur. This change in interpretation may be illustrated by the electron lines at 52.2, 53.0, and 57.6 kev which form a reasonable L_1, L_3, M group for a gamma ray at 59.0 kev. Previously the line at 53 kev was not resolved and had been assumed to be simply a K line for a gamma ray at 95 kev. Similarly the M line at 57.6 kev had been assumed to be a K line for a gamma ray at 100 kev. The line at 53 kev is as strong as that at 52.2 kev so it is probably both an L_3 line for the 59.0-kev gamma as well as a K line for the 95.0-kev gamma radiation.

There is evidence for Auger lines at low energy, but the electron line at 26.6 kev is too low in energy to be of this nature. The electron lines which yield the gamma ray at 40.8 kev could conceivably be of Auger origin as they correspond in energy to the difference in Pr work functions, K minus L minus M, and K minus M minus M. However, if these rather strong electron lines are of this nature then other stronger lines should be expected but are not found at lower energies, corresponding to such more probable transitions as K minus L_1 minus L_2.

TABLE II. Summary of gamma energies from Pr^{144}, in kev.

Observer EJK[a]	KC[b]	LJK[c]	PC[d]	Present
33.6	34.0		33.7	33.4
41.0	41.3			40.8
	46.8			
53.0	53.7	54.7	53.5	53.2
			60.3	59.0
80.2	80.9	79.4	80.7	79.9
94.8	95.0			95.0
99.6	100.5		100.3	
134.0	134.5	134	134.2	133.5
				145.2
		231		

[a] Emmerich, John, and Kurbatov, Phys. Rev. **82**, 968 (1951).
[b] H. Keller and J. Cork, Phys. Rev. **84**, 1079 (1952).
[c] Lin-Sheng, John, and Kurbatov, Phys. Rev. **85**, 487 (1952).
[d] F. Porter and G. Cook, Phys. Rev. **87**, 464 (1952).

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† This investigation received the joint support of the U. S. Atomic Energy Commission and the Office of Naval Research.
[1] D. Hahn and F. Strassman, Naturwiss. **28**, 543 (1940).
[2] See Hollander, Perlman, and Seaborg, "Table of Isotopes," Revs. Modern Phys. **25**, 469 (1953).

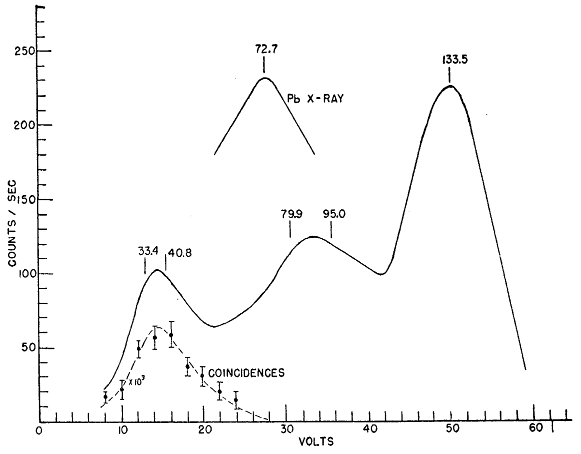

FIG. 1. Low-energy gamma rays in Pr^{144}, scintillation spectrometer.

The beta spectrum for Ce^{144} has been resolved by the aid of the double-focusing, constant-radius, magnetic spectrometer. The high-energy electrons due to the decay of Pr^{144} are always present and must be subtracted from the over-all distribution. The residual curve is complex and yields components with upper energy limits at 327±7 kev and 160±15 kev, whose relative abundances are 75 percent and 20 percent, respectively. There is good indication of another component with an upper energy limit of 258±15 kev and a relative abundance of about 5 percent. There could possibly still be some lower-energy component that is not seen because of the many conversion electrons.

With the scintillation spectrometer the low-energy peaks are not completely resolved. The 133.5-kev peak is relatively strong as shown in the singles curve of Fig. 1. The gamma-gamma coincidence curve between the 133.5-kev gamma ray and others at lower energies is also shown in Fig. 1. It is quite apparent that coincidence exists and hence the upper energy level representing the Pr^{144} nucleus must be higher than 134 kev as had been previously proposed.[2] The 133-kev gamma is in coincidence with both the 33- and 40-kev gammas. The 80-kev peak is also found to be in coincidence with both the 33- and 40-kev gamma with some evidence for a coincidence peak at 145 kev.

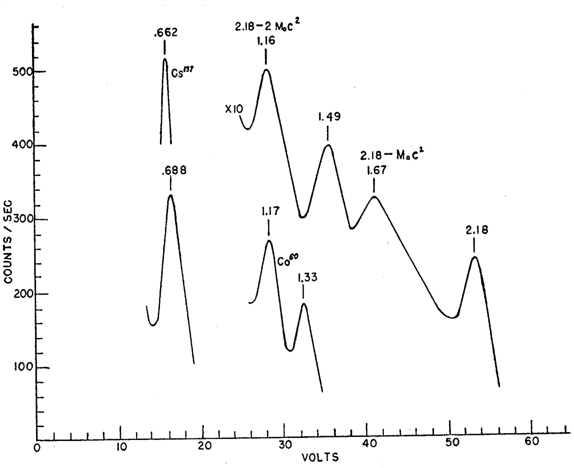

FIG. 2. High-energy gamma rays in Nd^{144}, scintillation spectrometer.

For the 133.5-kev gamma ray the K/L conversion ratio is found to be 5.8±0.5 and the L_3/L_1 ratio is small (~0.1) with no L_2 line present. It thus appears that this corresponds to an $M1$ transition although the K/L ratio is less than that expected from the empirical curves of Goldhaber and Sunyar. For the 79.9-kev gamma ray the K/L ratio is 3.0±0.5 and the L_3/L_1 ratio is small (~0.15), so that this is probably an $M2$ transition. The 59.0-kev gamma ray has a K/L ratio smaller than unity. If the L_3 line did not have a double interpretation the L_3/L_1 ratio would be about unity, since the L_3 line is almost as strong as the L_1 with no L_2 line present. This would then be a high-order magnetic multipole transition, probably designated as $M3$. In this event it should not be a prompt emission but the half-life of the initial state should be of the order of 100 seconds. This is presumably not the case.

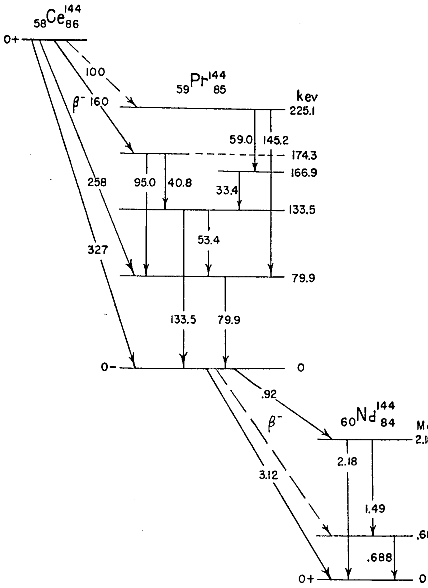

FIG. 3. Proposed nuclear level scheme for mass 144.

No conversion electron lines are observed that have energy differences corresponding to that of the work functions for neodymium. It is quite certain that the 60-kev gamma previously reported does not exist in this nucleus. Scintillation spectrometer observations of the high-energy region confirm, with some adjustment in energies, the previous reports.[3] The singles curve shown in Fig. 2 for this region yields energies at 0.688, 1.49, and 2.18 Mev. For the 2.18-Mev gamma ray, peaks due to the loss of both single and double annihilation radiation quanta are apparent. The upper energy limit of the beta spectrum is found to be at 3.12 Mev, a value somewhat higher than the previously

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[3] D. Alburger and J. Kraushaar, Phys. Rev. **87**, 448 (1952); C. Cook and W. Kreger, Bull. Am. Phys. Soc. **29**, No. 6, 20 (1954).

reported value of 2.97 Mev. A lower-energy component with a relative abundance of 1.5 percent has its upper energy limit at 0.92 Mev. No strong evidence appeared for the existence of a beta ray at an intermediate energy, as previously reported.[3]

The energies of certain gamma rays are observed to be equivalent to the sum of others, suggesting cross-over transitions. It is possible to postulate a reasonable nuclear level scheme for Pr^{144}, as shown in Fig. 3, which satisfies most of the observed data. The intensity relations as well as the coincidence data are about as would be expected from the level scheme.

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