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Gamma-Rays and Nuclear Levels Associated with Radioisotopes of Europium, Erbium, and Cerium*

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The energies of the conversion electrons associated with the decay of 8 radioisotopes were measured using permanent magnet-type photographic beta-spectrometers. The energies of the gamma-rays associated with the various activities are as follows: europium 152 (9.2-hr) 121.9, 344.1 kev; erbium 171 (7.5-hr) 112.8, 117.9, 125.5, 176.4, 294.5, 307.5, 419.7 kev; cerium 137 (36-hr) 253.4 kev; cerium 139 (140-day) 166.0, 275.2 kev; cerium 141 (28-day) 145.7 kev; cerium 143 (33-hr) 57.5, 290.6, 348.4 kev; cerium 144 (300-day) 34.0, 41.3, 46.8, 53.7, 80.9, 95.0, 100.5, 134.5 kev; and praseodymium 144 (17.5-min) 61.0 kev. Energy level schemes are proposed for each product nucleus.

THE evaluation of the energies of gamma-rays associated with short-lived radioactivities can best be carried out close to the source of the activation. For those radioactive isotopes arising from neutron capture, proximity to a pile is an advantage. Through the participating programs sponsored by the National Regional Laboratories, the heavy-water pile at Argonne was kindly made available for the present investigation.

APPARATUS AND METHOD

Spectrometers of the permanent-magnet-type, as previously described,[1] were located a few feet from the pile, so that a pneumatic tube could quickly transfer the irradiated specimens. Two magnets were employed and each was set at a different field value, such as 200 and 600 gauss, and each magnet accommodated two cameras. The camera box, as shown in Fig. 1, was provided with an auxiliary side tube portrayed in Fig. 2 which enabled the rapid injection of the activated specimen with no loss of vacuum. The action of the vacuum gate is as follows: (a) the specimen is placed in the source holder while the gate cover plate is removed, (b) the cover plate is put in position, and the forechamber rapidly evacuated, (c) when the forechamber is evacuated, the gate entrance to the camera is automatically opened by spring action, and (d) the specimen is pushed forward into its exact position within the

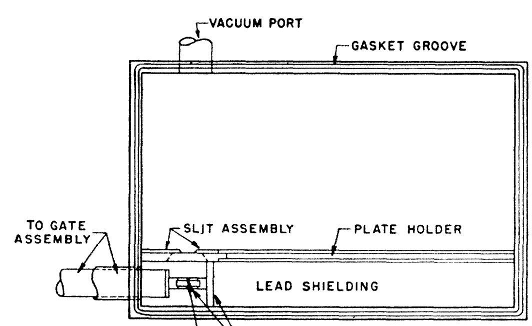

FIG. 1. The camera: a plan section drawing.

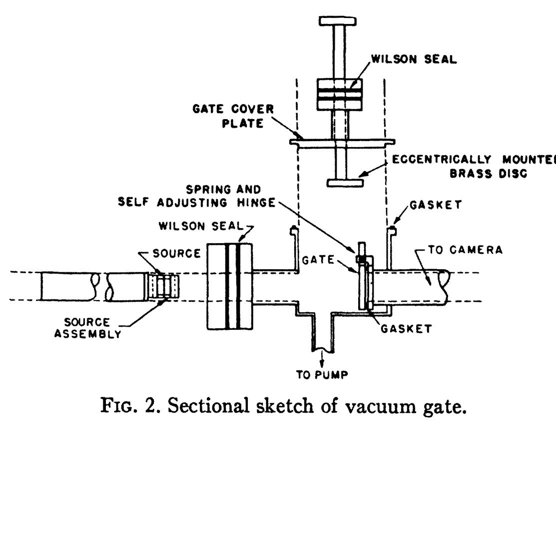

FIG. 2. Sectional sketch of vacuum gate.

* This project was aided by the joint support of the AEC and the ONR.

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[1] J. Cork, Phys. Rev. 72, 581 (1947).

TABLE I. The electron energies from Eu^{152}.

Electron energy	Proposed interpretation	Energy sum (kev)	Gamma-ray (kev)	Approx. K/L conversion ratio
75.0	K	121.9		
114.2	L_{I}	122.0		
114.6	L_{II}	121.9		
115.1	L_{III}	121.9		
120.3	M	122.0		
121.5	N	121.9	121.9	4
293.7	K	344.1		
336.2	L_{II}	344.2	344.1	10

camera. If necessary, repeated exposures may be made with no loss in line sharpness. Activities with half-life as short as 19 seconds have been successfully studied with this apparatus.

The magnetic fields were calibrated by the known energies of the electron lines in the radioactive decay of iodine 131, and at higher energies by the electron lines from a radium source. The enriched isotopes of cerium to be studied were supplied by the Oak Ridge National Laboratory. The powdered specimen, usually as an oxide, was made into a line source as massless as compatible with the required activity. Each line source was supported on a frame of very pure graphite, chosen because of its low neutron capture cross section in the pile. Eastman Kodak Type NTB photographic plates were used in the cameras. In addition to the various enriched isotopes of cerium, specimens of ordinary europium and erbium of high purity have been examined for their shorter-lived activities.

RESULTS

Europium 152

March and Sugden[2] were the first to report a 9.2-hour radioactivity in europium. Pool and Quill[3] using fast neutrons from the Michigan cyclotron concluded that the activity was in the isotope of mass 152. Tyler,[4] using a magnetic spectrometer, found the maximum beta-energy to be 1.9 Mev and three gamma-rays to

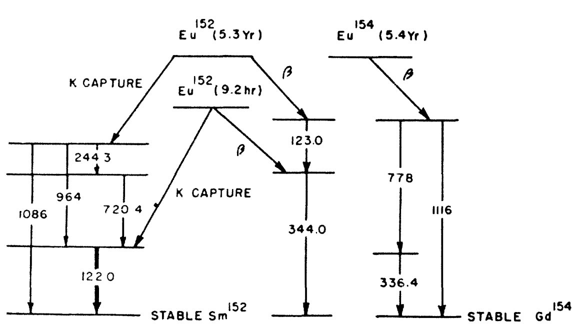

FIG. 3. Proposed level scheme of Gd^{154} and Sm^{152} following beta-emission and K-capture from Eu^{152} and Eu^{154}.

[2] J. Marsh and S. Sugden, Nature **136**, 102 (1935).
[3] M. Pool and L. Quill, Phys. Rev. **53**, 437 (1938).
[4] A. Tyler, Phys. Rev. **56**, 125 (1939).

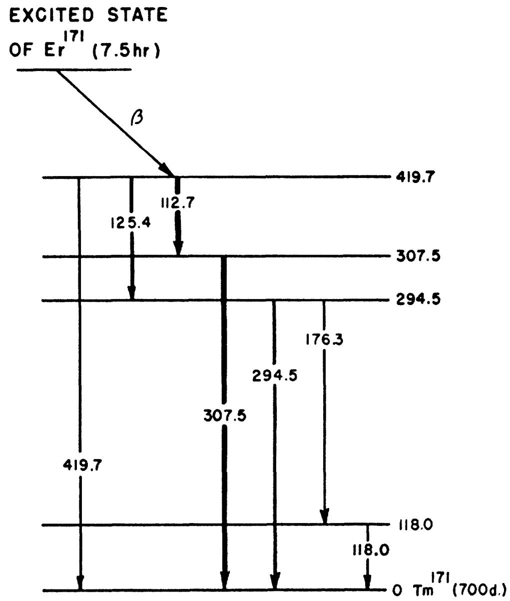

FIG. 4. Proposed level scheme of Tm^{171} following beta-emission from Er^{171}.

have energies 123, 163, and 725 kev. Muehlhause[5] showed that the K-capture process competes with beta-emission in the radioactive decay.

The europium used in the present investigation was brought from Munich by Dr. K. Fajans and is believed to be of very high purity. Two gamma-rays are found, one with an energy of 122.0 kev in samarium 152 following K-capture and another of 344 kev in gadolinium 152 following beta-emission. The electron energies together with their interpretation are shown in Table I. It had been shown[6] by mass spectrometer studies that a 5.3-year radioactivity exists in both Eu^{152} and Eu^{154}, and

TABLE II. Electron energies from Er^{171}.

Electron energy	Proposed interpretation	Energy sum (kev)	Gamma-ray (kev)	Approx. K/L conversion ratio
53.2	K	112.7		
103.1	$L_{I,II}$	112.7		
110.5	M	112.8	112.8	10
58.2	K	117.7		
108.3	$L_{I,II}$	117.9		
115.6	M	117.9	117.9	0.5
66.0	K	125.5		
116.0	$L_{I,II}$	125.6		
123.2	M	125.5		
125.0	N	125.5	125.5	2
116.9	K	176.4	176.4	...
234.8	K	294.3		
285.0	$L_{I,II}$	294.6	294.6	10
248.0	K	307.5		
298.2	$L_{I,II}$	307.8	307.5	10
360.2	K	419.7	419.7	...

[5] C. Muehlhause, Plutonium Project Report CP-3750, 46 (1947), unpublished.
[6] Hayden, Reynolds, and Inghram, Phys. Rev. **75**, 1500 (1949).

TABLE III. Relative abundance of the cerium isotopes.

Isotope	Normal	Ce^{136}	Ce^{138}	Ce^{140}	Ce^{142}
136	0.19%	8.94%	0.10%	0.02%	0.02%
138	0.26	0.81	4.42	0.02	0.06
140	88.47	84.98	92.00	99.25	16.51
142	11.08	5.27	3.48	0.71	83.42

hence one of these is isomeric with the 9.2-hour activity. A decay scheme had been previously proposed,[7] which, without separated isotopes, could not be established conclusively. An interchange of the gamma-spectra assigned to Eu^{152} and Eu^{154} now appears justified, as shown in Fig. 3.

Erbium 171

The erbium used in this investigation is a portion of the high purity material obtained by Dr. M. Goldhaber from the Oak Ridge Laboratory. An analysis showed no impurities present in amounts beyond the sensitivity limit of the spectrographic method.

The hypothesis of Ketelle and Peacock[8] that erbium 169 decays with a 9.4-hour half-life by beta-emission without gamma-radiation, is confirmed. Erbium 171 decays with a half-life of 7.5 hours. Only two of the previously reported three gamma-rays were found. The third, a high energy gamma-ray (805 kev), was not observed. In addition, five previously unreported gamma-rays were detected. The complete data are given in Table II. A proposed decay scheme is presented in Fig. 4.

TABLE IV. The electron energies from Ce^{137}.

Electron energy	Proposed interpretation	Energy sum (kev)	Gamma-energy (kev)	Approx. K/L conversion ratio
214.5	K ($Z=57$)	253.2		
247.6	L	253.4		
252.0	M	253.5	253.4	10

A Survey of the Radioisotopes of Cerium

Cerium has four stable isotopes, all of even mass numbers. It is thus possible that neutron capture in each will result in a radioactive isotope of odd mass number. In order to facilitate a comprehensive study of the element, stable enriched isotopes of each mass were procured from Oak Ridge. The relative abundance of the isotopes as they occur naturally, and in each of the enriched masses is shown in Table III.

TABLE V. Electron energies from Ce^{139}.

Electron energy	Proposed interpretation	Energy sum (kev)	Gamma-energy (kev)	Approx. K/L conversion ratio
127.4	K ($Z=57$)	166.1		
160.1	L	166.0	166.0	10
236.5	K	275.2	275.2	...

1. Cerium 137

The existence of an activity in cerium with a 36-hour half-life was first reported by Chubbuck and Perlman[9] as the result of a (d, $4n$) reaction by the bombardment of lanthanum with forty-Mev deuterons in the Berkeley 184-inch cyclotron. By absorption of electrons in beryllium they reported a conversion electron peak at 230 kev. They found no evidence for positron activity but did report finding x-rays characteristic of lanthanum, and therefore assumed the decay to be by K-electron capture. Absorption of the electromagnetic radiations in lead yielded gamma-rays of energies 280 and 750 kev.

TABLE VI. Electron energies from Ce^{141}.

Electron energy	Proposed interpretation	Energy sum (kev)	Gamma-energy (kev)	Approx. K/L conversion ratio
103.7	K ($Z=59$)	145.7		
138.8	L	145.6		
144.2	M	145.7	145.7	>1

A spectrogram of the 36-hour period of cerium 137 showed three electron lines due to a single gamma-ray of energy 253.4 kev. The sample used was the separated isotope of cerium 136. In normal cerium it occurs with an abundance of 0.2 percent; in the separated isotope it was 8.94 percent abundant, an increase by a factor of 45.

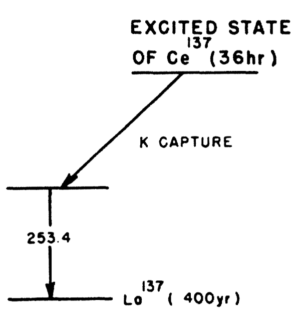

FIG. 5. Proposed level scheme for La^{137} following K-capture from Ce^{137}.

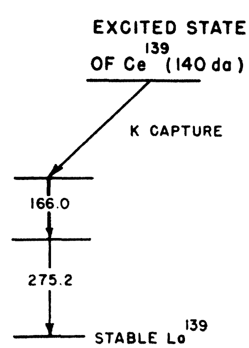

FIG. 6. Proposed level scheme for La^{139} following K-capture from Ce^{139}.

[7] Cork, Keller, Rutledge, and Stoddard, Phys. Rev. **77**, 848 (1950).

[8] B. Ketelle and W. Peacock, Phys. Rev. **73**, 1269 (1948).

[9] J. Chubbuck and I. Perlman, Phys. Rev. **74**, 982 (1948).

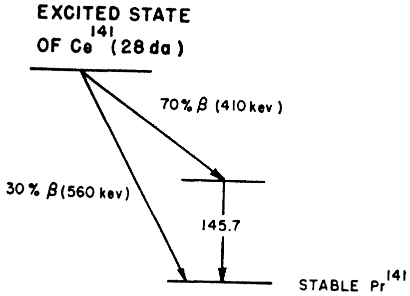

FIG. 7. Proposed level scheme for Pr^{141} following beta-emission from Ce^{141}.

Table IV gives the energies of the electron lines as they were observed, along with their interpretation. The proposed decay scheme is given in Fig. 5.

2. *Cerium 139*

Matthews and Pool[10] were the first to assign the 140-day activity in cerium to the isotope 139. They produced the activity by a (*d*, *n*) reaction on lanthanum and established *K*-electron capture by photographing the x-ray spectrum of the activity and finding the $K\alpha$ line of lanthanum. Further investigations of the activity were carried out by Pool and Krisberg.[11] They found spectrographic evidence for a gamma-ray of about 175 kev and on the basis of lead absorption curves reported a gamma-ray of about 800 kev.

Spectrograms of this activity, derived from the slow neutron bombardment of the separated isotope cerium 138, yielded conversion lines indicative of two gamma-rays of energies 166.0 and 275.2 kev. In Table V are given the energies and interpretations of the lines. A simple decay scheme is proposed in Fig. 6.

3. *Cerium 141*

Of the activities in cerium it is probably cerium 141 with a half-life of about 30 days that has most often been investigated. Ter-Pogossian, *et al.*,[12] investigated the photoelectric as well as the conversion spectrum and reported gamma-rays of 146 and 315 kev. They indicated that the beta-spectrum is complex but did not attempt an evaluation of the components. Shepherd[13] expressed the beta-components as 0.41 and 0.56 Mev, and a single gamma-ray of 141 kev. A survey[14] was conducted especially to verify the existence of the previously reported unconverted gamma-ray at 315 kev, with negative results. The instrument used for this survey was a sodium iodide proportional scintillation counter and a 20-channel pulse discriminator. A summary of the electron line spectrum is presented in Table VI, and the proposed simple-level scheme is portrayed in Fig. 7.

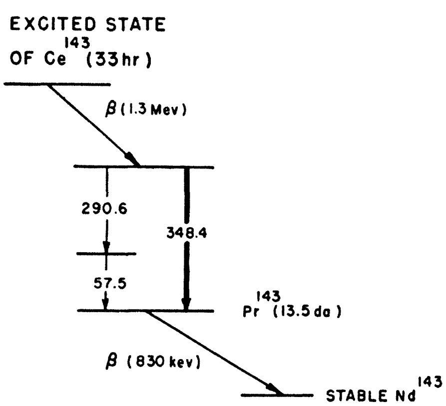

FIG. 8. Proposed level scheme for Pr^{143} following beta-emission from Ce^{143}.

TABLE VII. Electron energies from Ce^{143}.

Electron energy	Proposed interpretation	Energy sum (kev)	Gamma-energy (kev)	Approx. *K/L* conversion ratio
15.6	*K* (*Z*=59)	57.6		
50.7	*L*	57.5		
55.9	*M*	57.4	57.5	<1
248.5	*K*	290.5		
284.2	*L*	290.7	290.6	10
306.4	*K*	348.4	348.4	···

4. *Cerium 143*

A 33-hour activity was first produced by bombarding normal cerium with either deuterons or neutrons[3] and assigned to mass 143. Various investigators,[10] using absorption techniques, report a 1.3-Mev beta-ray and a 550-kev gamma-ray.

An enriched isotope of cerium 142 (83.4 percent) was

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

Electron energy	Proposed interpretation	Energy sum (kev)	Gamma-energy (kev)	Approx. *K/L* conversion ratio
27.2	L_I (*Z*=59)	34.0		
32.5	*M*	34.0	34.0	···
34.5	L_I	41.3	41.3[a]	···
40.0	L_I	46.8	46.8	···
11.7	*K*	53.7		
47.0	L_I	53.8	53.7	<1
38.8	*K*	80.8		
74.1	L_I	80.9		
79.4	*M*	80.9		
80.6	*N*	80.9	80.9	5
53.0	*K*	95.0	95.0	···
58.5	*K*	100.5	100.5	···
92.4	*K*	134.4		
127.8	L_I	134.6		
133.0	*M*	134.5		
134.1	*N*	134.4	134.5	10

[a] M masked by the heavy line at 40.0 kev.

[10] D. Matthews and M. Pool, Phys. Rev. **72**, 163 (1947).
[11] M. Pool and N. Krisberg, Phys. Rev. **73**, 1035 (1948).
[12] Ter-Pogossian, Cook, Goddard, and Robinson, Phys. Rev. **76**, 909 (1949).
[13] L. R. Shepherd, Research (London) **1**, 671 (1948).
[14] B. Hamermesh (private communication).

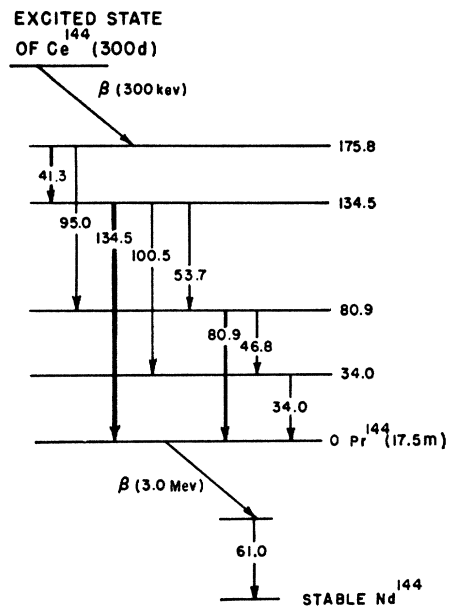

FIG. 9. Proposed level scheme for Pr^{144} and Nd^{144} following beta-decay from Ce^{144}.

irradiated in the reactor and observed. Three gamma-rays were found, none of which approximated the previously reported value of 550 kev. The electron energies and their interpretation are given in Table VII. Figure 8 is a proposed level scheme showing the decay to excited Pr^{143} which in turn decays by beta-emission to stable Nd^{143}.

5. *Cerium 144*

An activity in cerium derived from the fission of uranium has been reported[15] by several investigators to have a half-life of about 300 days. It is beta-active with an end point of about 300 kev, but no gamma-rays had been found in the radiation. The source used in the present study was a fission product obtained from Oak Ridge and was carrier-free, with a very high specific activity. The sources were prepared from an active solution and mounted as thin-etch lines on conducting films. Many conversion electron lines were observed and their energies together with their interpretations are assembled in Table VIII. The eight observed gamma-rays fit remarkably well the nuclear level scheme presented in Fig. 9.

TABLE IX. Electron energies from Pr^{144}.

Electron energy	Proposed interpretation	Energy sum (kev)	Gamma-ray (kev)	Approx. K/L conversion ratio
17.3	K ($Z=60$)	60.9		
53.8	L_I	61.0		<1
59.4	M	61.0	61.0	

6. *Praseodymium 144*

Praseodymium 144 is[16] the 17.5-minute half-lived daughter of cerium 144. It decays[17] by the emission of a 3-Mev beta-particle to an excited state of stable neodymium 144. The excited state then transforms to the stable element with the emission of a 61.0-kev gamma-ray. This value does not agree with that found by the absorption methods of other investigators. The experimental data for the electron conversion lines appear in Table IX. The proposed decay appears along with that of cerium 144 in Fig. 9.

The authors are deeply indebted to Drs. L. A. Turner, J. C. Boyce, C. O. Muehlhause, S. B. Burson, and others of the Argonne staff for their kind and helpful interest in this work.

[15] H. Born and W. Seelmann, Eggebert, Naturwiss. **31**, 201 (1943); V. Nedsel and M. Sampson, Plutonium Project Report CC-2283, 1944, and others.

[16] O. Hahn and F. Strassmann, Naturwiss. **31**, 499 (1943), and others.

[17] Peacock, Jones, and Overman, Plutonium Project Report, Mon. N. 432 (1947).