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

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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 ($\sim$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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[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).

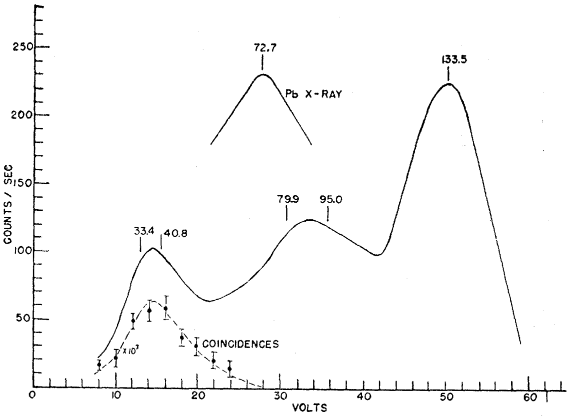

FIG. 1. Low-energy gamma rays in Pr^{144}, scintillation spectrometer.

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.

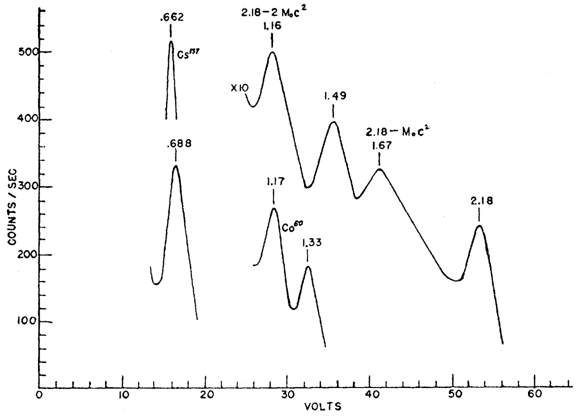

FIG. 2. High-energy gamma rays in Nd^{144}, scintillation spectrometer.

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.

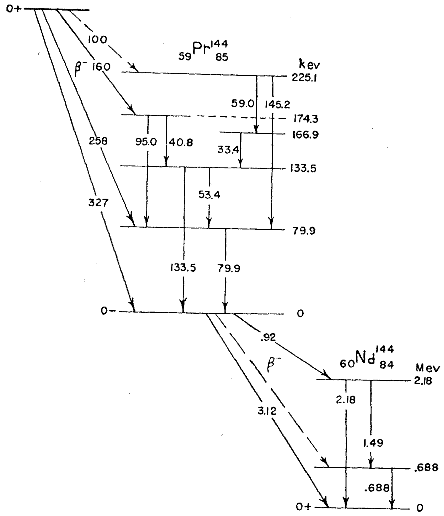

FIG. 3. Proposed nuclear level scheme for mass 144.

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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Slow Neutron Cross Sections of Gold, Silver, Indium, Nickel, and Nickel Oxide

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The total reflection and selective attenuation properties of mirrors for neutrons were used to obtain essentially higher order free reflections of a beam of reactor neutrons from a quartz crystal. An arrangement of mirror, crystal, and sample, in series was used to measure the total cross section of Au, Ag, In, Ni, and NiO as a function of neutron wave length over intervals in the region between 0.7A and 4.6A. The results on the strong absorbers Au, Ag, and In were analyzed into absorption and scattering contributions. The absorbers exhibited essentially the $1/v$ characteristic expected. The scattering and absorption cross sections of Au, Ag, and In are compared with previously reported values. For the strong scatterers Ni and NiO, the total scattering, ordered scattering, and disordered scattering cross sections, and the Debye temperature were derived from the energy dependence of the total cross section. The ordered scattering cross section per Ni nucleus was found to be 13.1±0.3 barns. The capture and ordered elastic contributions were subtracted from the experimental curve of total cross section *vs* energy. This residual scattering function of energy was compared to that theoretically expected from a Debye independent-oscillator model and the one-phonon incoherent scattering approximation of Kleinman. In the case of Ni, at the longer wavelengths, both models fit the data well, and at the shorter wavelengths, where multiple phonon processes occur, the independent oscillator model continues to fit the data. For NiO, measurements fit the independent oscillator model at the shorter wavelengths, and lie above the values calculated from either model at the longer wavelengths. Additional measurements of the total cross section of NiO as a function of temperature would be needed to attribute the difference between measured and calculated values at the longer wavelengths definitely to inelastic scattering processes.

I. INTRODUCTION

THE development of high-intensity neutron sources, such as chain reactors, and the utilization of the wave properties of neutrons for diffraction from single crystals provide a relatively simple instrument, the neutron spectrometer, for obtaining nearly monoenergetic neutron beams of usable intensities. The intensity distribution in the neutron spectrum from slow neutron chain reactors is such that, for most commonly used crystals, higher order reflections from the crystal must be considered in certain regions of the spectrum. Bragg's law $n\lambda = 2d\sin\theta$ states that for a fixed angle of incidence, wavelengths λ, $\lambda/2$, $\lambda/3$, $\cdots$, having energies E, $4E$, $9E$, $\cdots$, will be present in the beam reflected from a crystal. Since the energy spectrum from a chain reactor is approximately Maxwellian, the presence of the higher orders may not be troublesome at glancing angles corresponding to first order energies E greater than the most probable energy, because the neutron flux decreases rapidly with increasing energy. For energies less than the most probable energy, the presence of higher orders can be very troublesome. The higher order crystal reflections can be removed by use of the total reflection properties of mirrors. (We find that a mirror was used briefly for this purpose in 1945 by L. B. Borst and associates.[1])

The reflectivity of a plane mirror for neutrons of wavlength λ is given by

$$R = \left\{ \frac{1-[1-(\lambda/\lambda_f)^2]^{\frac{1}{2}}}{1+[1-(\lambda/\lambda_f)^2]^{\frac{1}{2}}} \right\}^2, \tag{1}$$

where λ_f, the cut-off or critical wavelength is related to the glancing angle of incidence on the mirror, α, by the expression:

$$\lambda_f = \frac{\alpha}{(N\bar{f}/\pi)^{\frac{1}{2}}}. \tag{2}$$

Here, N is the number of nuclei per cm^3 of the mirror material and $\bar{f}$ is the average ordered (coherent) scattering amplitude, due regard being taken of the signs of the individual scattering amplitudes. For a fixed angle of incidence, wavelengths greater than the cut-off wavelength will be totally reflected, whereas the inten-

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[1] Borst, Ulrich, Osborne, and Hasbrouck, Atomic Energy Commission Report MDDC 15 (unpublished).