Decay of Ce^{144} and Pr^{144}†

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The beta and gamma spectra from the decay of Ce^{144} and Pr^{144} have been investigated by means of a magnetic-lens beta spectrometer and single-channel scintillation spectrometers. Three partial beta spectra with end-point energies and relative intensities of 184 kev (30%), 245 kev (5%), and 320 kev (65%) were observed for Ce^{144}. Gamma rays and internal conversion lines corresponding to 54, 80, and 134-kev transitions were also detected. Internal conversion coefficients indicate an $M1$ multipolarity for the 80- and 134-kev transitions. Pr^{144} yields three partial beta spectra with end-point energies and relative intensities of 0.90 Mev (2%), 2.45 Mev (3%), and 3.15 Mev (95%). Corresponding gamma rays were also detected. Beta-gamma and gamma-gamma coincidence measurements substantiate the proposed decay scheme.

INTRODUCTION

THE disintegration schemes for Ce^{144} and Pr^{144} have been previously measured by several investigators,[1–5] but analysis of the data has shown that a number of inconsistencies are evident. Major uncertainty appears in the delineation of the number of excited states of Pr^{144} and the energy of the highest state of excitation. The highest excited state has been reported as occurring at 134 kev,[1] 174 kev,[4] and 225 kev.[3] The present work was undertaken in an attempt to resolve some of the apparent contradictions.

EXPERIMENTAL TECHNIQUE

Measurements of the beta-ray and the beta-gamma coincidence spectra were made on a magnetic-lens spectrometer connected in coincidence with a single-channel gamma-ray scintillation spectrometer. Gamma-gamma coincidence spectra were observed by use of two single-channel scintillation spectrometers connected in coincidence. The magnetic-lens spectrometer had a momentum resolution of 3% at a transmission of approximately 0.5%. The negative beta particles were detected with a scintillation counter utilizing a thin anthracene crystal.

The Ce^{144} and Pr^{144} was obtained carrier-free from the Oak Ridge National Laboratory in the form of $CeCl_3$ in HCl solution. Sources were prepared by evaporation of the solution on a mica disk, approximately 1 mg/cm^2 thick, which was mounted on an aluminum grounding ring. Beta rays from S^{35} sources prepared in this manner yielded linear Kurie plots down to 80 kev and indicated that the detector was sensitive to electrons with energies greater than 8 kev.

The gamma-ray spectrometer associated with the lens spectrometer utilized a 1-in. diameter by 1-in. thick NaI(Tl) crystal mounted on an RCA 5819 photomultiplier tube. Signals were fed through a linear amplifier to a single-channel pulse-height analyzer. Energy resolution of the 662-kev gamma-ray peak emitted by Ba^{137} was less than 10% (full width at half-amplitude). Similar instrumentation was used on the two-channel coincidence gamma-ray spectrometer.

Fast-slow coincidence techniques were used for beta-gamma coincidence measurements to shorten the resolving time beyond that obtainable without by-passing the slow pulse-height analyzer. The resolving time of the fast coincidence circuit could be made as short as 5×10^{-8} sec. In the two-channel gamma-ray spectrometer, coincidences were determined after pulse-height analysis and the circuit was operated at a resolving time of 2×10^{-7} sec.

RESULTS

A. Beta-Ray and Gamma-Ray Spectra

The beta spectrum of Pr^{144} was resolved into three components as shown in Fig. 1(a). The characteristics of the partial spectra are tabulated in Table I. The subsequently emitted gamma rays with energies of 0.69 Mev, 1.5 Mev, and 2.2 Mev were also detected. The results are in agreement with previous measurements.[2–4]

Kurie plots of the Ce^{144} beta spectrum [Fig. 1(b)] show the existence of three partial spectra whose characteristics are given in Table I. Two strong conversion lines were also observed and are attributed to K conversion of 134-kev and 80-kev gamma transitions.

TABLE I. Characteristics of observed beta spectra.

Parent isotope	End-point energy (kev)	Relative intensity	Log ft
Pr^{144}	3150±100	95±4	6.7
Pr^{144}	2450±100	3±2	7.8
Pr^{144}	900± 50	2±1	6.0
Ce^{144}	320± 10	65±5	7.5
Ce^{144}	245± 15	5±3	8.2
Ce^{144}	184± 10	30±5	7.1

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1 I. Pullman and P. Axel, Phys. Rev. **102**, 1366 (1956).
2 Cork, Brice, and Schmid, Phys. Rev. **96**, 1295 (1954).
3 W. E. Kreger and C. S. Cook, Phys. Rev. **96**, 1276 (1954).
4 Emmerich, Auth, and Kurbatov, Phys. Rev. **94**, 110 (1954).
5 References to earlier works are given in references 1–4.

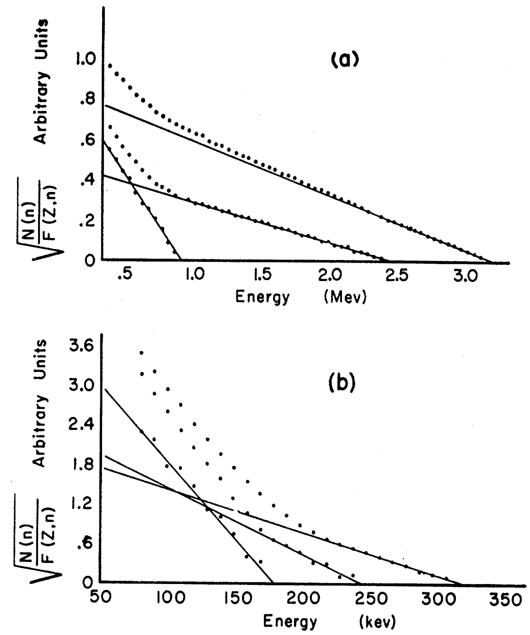

FIG. 1. Kurie plots of the observed beta spectra. The three partial spectra attributed to the decay of Pr^{144} are shown in (a), the spectra associated with the decay of Ce^{144} are shown in (b).

Weak K and L conversion lines corresponding to a 54-kev transition were also detected.

In Fig. 2 is shown the low-energy gamma-ray spectra associated with the decay of Ce^{144} as obtained with the scintillation spectrometer. Subtraction of Gaussian curves fitted to the peaks at 134 kev and 36 kev yields a third peak centered at 80 kev. This residual peak is somewhat broader than expected and may indicate the existence of weak unresolved transitions, but the resolution of the scintillation spectrometer does not justify any further interpretation. Gamma-ray intensity ratios were obtained by comparison of the photopeak areas after correction for NaI(Tl) crystal efficiency,[6] iodine x-ray escape,[7] and absorption in a Lucite plug which

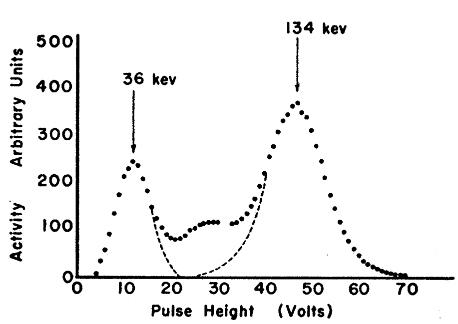

FIG. 2. The low-energy gamma-ray spectra emitted by Pr^{144}.

[6] P. R. Bell, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. V.

[7] P. Axel, Rev. Sci. Instr. **25**, 391 (1954).

was used to prevent high-energy beta rays from entering the crystal. The ratio of unconverted intensities of the 134-kev and 80-kev gamma rays and the 36-kev x-ray is 100:32:107.

B. Coincidence Spectra

Kurie plots of the beta-ray spectra in coincidence with the 134-kev and 80-kev gamma rays and the 36-kev x-ray are shown in Fig. 3. In all three cases, the main beta component has an end-point energy of 180 ± 20 kev, but the spectra coincident with the 80-kev gamma ray and the 36-kev x-ray show a high-energy tail extending up to approximately 240-kev. Analysis of the 80-kev coincidence spectra indicates that the 80-kev transition is fed 75% of the time by the 180-kev

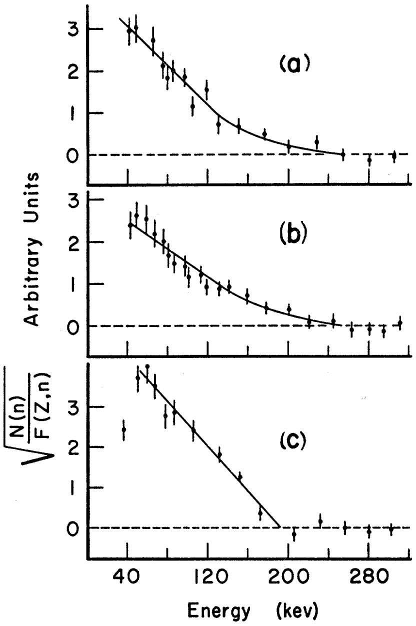

FIG. 3. Kurie plots of the beta spectra coincident with the various gamma rays. (a) Coincident with the 36-kev x-ray; (b) coincident with the 80-kev gamma ray; (c) coincident with the 134-kev gamma ray.

beta-ray group and 25% of the time by the 240-kev beta-ray group.

No gamma rays were found to be in coincidence with the 134-kev transition. In Fig. 4 is shown the gamma-ray spectrum coincident with the 80-kev transition, indicating the existence of an x-ray peak and a rather smeared peak centered at approximately 54 kev.

ANALYSIS

A. Conversion Coefficients

The K-conversion coefficients for the 80-kev and the 134-kev gamma rays were obtained by comparing the gamma-ray intensities with the associated x-ray intensity after correcting for the fluorescence yield[8] of Pr. The area of the internal conversion lines, as obtained with the lens spectrometer, were used as a guide to determine the fraction of the x-ray peak associated with the particular gamma ray. The values of the conversion coefficients are given in Table II together with the theoretical values of Sliv and Band.[9] The experimental values are in agreement with previously reported measurements.[1] Both transitions have been tentatively assigned $M1$ multipolarities even though the agreement between the experimental and theoretical conversion coefficients is not as good as one would like.

Combining the internal conversion coefficients, unconverted gamma-ray intensities, and the partial beta-ray intensities yields the following percentages for the transition probabilities per disintegration:

$$I_{134}=(23\pm3)\%,$$
$$I_{80}=(10\pm2)\%.$$

It is possible to obtain a conversion coefficient for the 54-kev transition from the gamma-gamma coincidence spectra under the assumption that the smeared peak at 54 kev is due to a single gamma ray. The results of this analysis yields $\alpha_K^{54}=1.7\pm0.5$ which indicates an

TABLE II. K-conversion coefficients.

Gamma-ray energy (kev)	Experimental	Theoretical $E1$	$M1$	$E2$	$M2$
134	0.76±0.15	0.110	0.553	0.582	4.11
80	1.40±0.24	0.440	2.38	2.49	26.4

$E1$ assignment for the transition. Assignment of $M1$ to the 80-kev and 134-kev transitions implies that these two states have the same parity and that the transition between them must not be accompanied by a parity change. This would rule out an $E1$ assignment for the 54-kev transition and suggests that the assumption of a single gamma ray producing the smeared 54-kev peak in the coincidence spectra is not a valid assumption.

B. Decay Scheme

Present measurements on the decay of Pr^{144} are in agreement with previously reported decay schemes[2,3] and will not be discussed here. It was not possible to determine the gamma-ray multipolarities; consequently, no experimental information is available concerning the spin and parity assignments for the excited states of Nd^{144}.

In the case of the decay of Ce^{144}, the absence of any gamma-rays coincident with the 134-kev transition and the single coincident beta-ray group indicates that the 134-kev level is the highest level excited in Pr^{144}. The beta spectra coincident with the 80-kev transition indicates that it is predominantly fed (75% of the time) by cascade from the 134-kev level, but there is also a direct beta-ray transition to an 80-kev level in Pr^{144}. A decay scheme consistent with these observations is shown in Fig. 5.

The observed beta-ray branching ratio and the measured intensities for the 80-kev and 134-kev transitions imply an absolute intensity for the 54-kev transition of 7.5±4%. This is somewhat higher than would be expected from the observed gamma-ray spectra, but, due to the difficulty of separating the 54-kev transition from the more intense 80-kev and 36-kev peaks, no experimental measurement of the gamma-ray intensity is available. The ratio of the implied 54-kev transition intensity to that of the 134-kev transition is in fair agreement with the ratio of single-particle model transition probabilities[10] for $M1$ transitions, which vary as the cube of the energy.

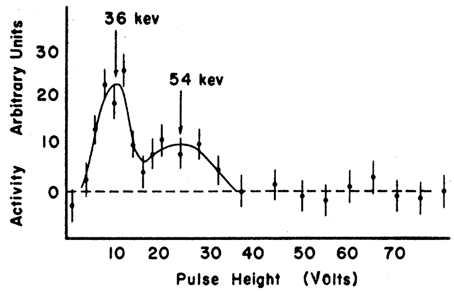

FIG. 4. Gamma-ray spectra coincident with the 80-kev transition.

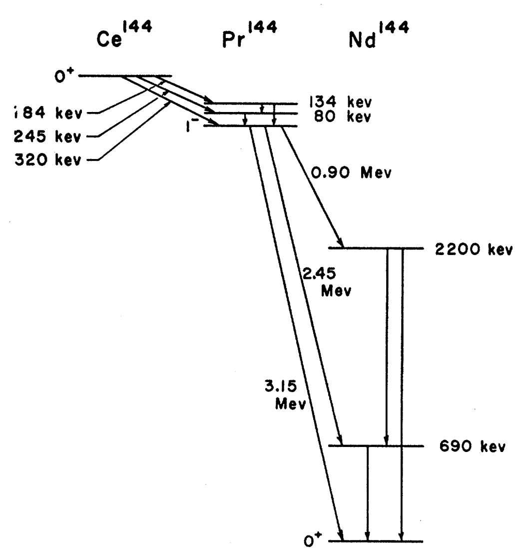

FIG. 5. Proposed decay scheme for Ce^{144} and Pr^{144}.

[8] I. Bergström, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. XX.

[9] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 (unpublished) [translation: Report 57 ICC K1, Physics Department, University of Illinois (unpublished)].

[10] S. A. Moszkowski, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 391; J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. XII.

A search with a proportional counter and a scintillation counter spectrometer, for a 12-kev transition that has been proposed as existing in a 42-kev—12-kev[1] cascade, yielded negative results. The existence of the 12-kev gamma ray seems unlikely, but due to the complex gamma spectra in the neighborhood of 42 kev, the possible existence of a 42-kev transition can not be denied. The possible existence of an unresolved 192-kev beta group, which would feed the 80-kev level in Pr^{144} by the emission of a 42-kev gamma ray, is certainly not ruled out and would help explain the small observed intensity for the 54-kev transition. The smearing of the 54-kev peak in the gamma-gamma coincidence spectra lends some support to this hypothesis.

The reported 100-kev—34-kev gamma-ray cascade[1] is neither confirmed or denied, but the present measurements indicate that the intensity of this cascade must be less than 5% of the intensity of the 134-kev transition.

The parent isotope, Ce^{144}, is an even-even nucleus and is expected to have a 0^+ configuration for its ground state. All three beta spectra emitted by Ce^{144} are characterized by high $\log ft$ values (Table I), suggesting first forbidden transitions. The observed states in Pr^{144} would then be characterized by odd parity and spins of either 0, 1, or 2. The ground-state characteristics of the odd-odd nucleus Pr^{144} are not uniquely determined by the shell model,[11] but the predictions call for odd parity and a minimum spin of one. The odd neutron and odd proton most likely occupy $f_{7/2}$ and $d_{5/2}$ levels respectively, yielding a possible 1^- configuration for the ground state. A 1^- assignment for the ground state and either a 1^- or 2^- assignment for the excited states is consistent with first forbidden beta-decay selection rules and with $M1$ or $E2$ gamma-ray transitions.

The 1^- assignment is in disagreement with recent measurements on the shape of the Pr^{144} beta spectra which have indicated that the ground state of this nucleus should be given a 0^- assignment. Brosi and Ketelle[12] found a unique "2, yes" shape for the Pr^{144} beta spectra coincident with the 0.69-Mev gamma ray. Assigning a 2^+ classification to the 0.69-Mev level in Nd^{144} on the basis of being the first excited state of an even-even nucleus, leads then to a 0^- assignment for the Pr^{144} ground state. This has been substantiated[13] by the determination of a unique correction factor corresponding to a 0^- to 0^+ transition for the beta spectrum between the ground states of Pr^{144} and Nd^{144}.

A possible shell-model configuration yielding a 0^- assignment for the ground state for Pr^{144} would be obtained by assigning the odd proton to the $g_{7/2}$ level, but the odd-proton nuclei Pr^{141} and Pr^{143} both have spins of 5/2 with the odd proton assigned to the $d_{5/2}$ level.[11] Difficulty arises in trying to understand how the addition of one or three neutrons can cause the odd proton to jump from the $d_{5/2}$ level to the $g_{7/2}$ level. It should be pointed out, however, that the present experimental data are not in disagreement with a 0^- assignment for the Pr^{144} ground state.

ACKNOWLEDGMENTS

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[11] J. H. D. Jensen, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 414.

[12] A. R. Brosi (private communication).

[13] M. J. Laubitz, Proc. Phys. Soc. (London) **A69**, 789 (1956).