Radiations of Ce^{143}†

W. H. BURGUS
Los Alamos Scientific Laboratory, Los Alamos, New Mexico
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A spectrometric investigation of the radiations of Ce^{143} has revealed that there are beta-ray groups of 1.090±0.005, 1.390±0.005, and 0.710±0.010 Mev maximum energy. In addition, there was evidence for a fourth lower energy group which could not be resolved. Electromagnetic radiations of energies 0.0349 ±0.001, 0.126±0.005, ~0.160±0.010, 0.289±0.005, 0.356±0.005, 0.660±0.010, and 0.720±0.010 Mev were found. A decay scheme for Ce^{143} is proposed.

I. INTRODUCTION

EARLY studies of the radiations of Ce^{143} using absorption methods showed the presence of a beta-ray of maximum energy ~1.36 Mev[1–3] and gamma-rays of energy about 0.5 Mev[1] or 0.6 Mev.[3] Later absorption and coincidence studies[4] indicated additional gamma-rays of 0.040, 0.20, and 0.89 Mev. More recent spectrometric studies[5] have shown gamma-rays of 0.0575, 0.2906, and 0.3484 Mev, obtained through observation of internal conversion lines. A recent spectrometric investigation[6] of the beta-spectrum has revealed that there are at least two beta-groups of 1.09 and 1.37 Mev with indications of a third of lower energy, about 0.37 Mev. Also found[6] were gamma-rays of energy 0.705, 0.649, 0.283, 0.057, and 0.0354 Mev.

In the present investigation the radiations of Ce^{143} have been examined in a magnetic lens spectrometer and in a sodium iodide scintillation spectrometer, with a few gamma-gamma coincidence experiments employing two sodium iodide scintillators. The Ce^{143} sources employed were prepared both by pile irradiation of cerium oxide enriched in Ce^{142} and by isolation from fission product mixtures. The enriched Ce^{142} was obtained through the Isotopes Division of the U. S. Atomic Energy Commission and showed the following mass analysis: Ce^{136}—0.016 atom percent; Ce^{138}—0.055 atom percent; Ce^{140}—16.51 atom percent; Ce^{142}—83.42 atom percent. The principal impurity listed for the samples was 0.15 percent gadolinium. To remove radioactive gadolinium formed during neutron-irradiation of the cerium, three cerium-gadolinium chemical separations were made, employing lanthanum as a stand-in carrier for gadolinium. The chemical procedure used was based on the cerium-rare earth separation commonly employed,[7] i.e., precipitation of ceric iodate from a strongly acidic solution leaving rare earths in the supernatant liquid. This procedure also served to remove all Pr^{143} grown from Ce^{143} during irradiation and during the time between the end of the irradiation and the beginning of chemical separations. The principal radioactive contaminant in Ce^{143} samples freshly prepared in this way was the Ce^{141}, which amounted to ~1 percent of the radioactive disintegrations in the sample. In the beta-spectrum, this impurity contributed only at energies below 0.581 Mev, the maximum beta-ray energy[8] of Ce^{141}. For the preparation of Ce^{143} sources from fission products, samples of uranium enriched in U^{235} were irradiated with thermal neutrons in a pile. To minimize the amount of Ce^{141} isolated along with Ce^{143}, advantage was taken of the difference in the half-lives of the La^{141} (3.7 hr)[9] and La^{143} (19 min)[10] parents, and the fact that Ce^{141} has a very low independent fission yield[11] while Ce^{143} has an independent fission yield of about 1.6 percent. (The total yields of Ce^{141} and Ce^{143} are 5.7 and 5.4 percent, respectively.[12]) With an irradiation of about one-half hour duration, followed by isolation of Ce within the next hour, Ce^{143} could be separated before much Ce^{141} had grown from La^{141}. Sources freshly prepared in this way contained small amounts of Ce^{141} activity but could be obtained in higher specific yield than when the Ce^{143} was made by neutron-irradiation of enriched Ce^{142}. A disadvantage of fission product sources was that in addition to Ce^{141} a small amount of Ce^{144} was also isolated along with the Ce^{143} (~0.5 percent of the total activity).

II. BETA-SPECTRA

The beta-ray spectrometer used in this study was a single coil magnetic lens type described in a previous paper from this laboratory.[13] In running the beta-spectra a resolution of about 2.5 percent was used, and a G-M counter with a 3.5-mg/cm² mica end window served as the detector.

Beta-spectra were taken with two kinds of sources. The $Ce^{142}(n,\gamma)Ce^{143}$ sources consisted of approximately 6 mg of cerium oxide spread over an area of ~0.3 cm² and mounted on a 0.3-mil Dural backing. The source was cemented to the backing with a drop of ~20-to-1

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[13] L. Langer, Phys. Rev. **77**, 50 (1950).

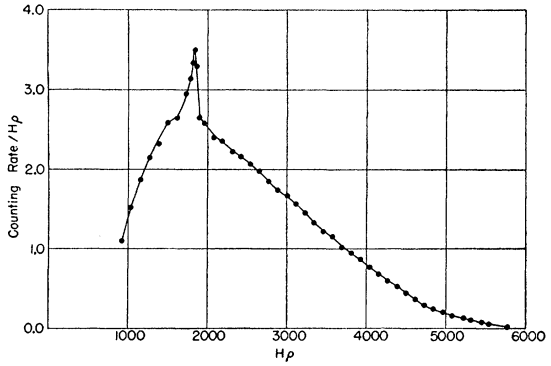

FIG. 1. Electron spectrum of Ce^{143}.

acetone dilution of Duco cement added to the powdered CeO_2 and allowed to dry under a heat lamp. The fission product Ce^{143} sources consisted of ~1 mg of CeO_2 mounted in a similar manner over about the same area. The spectrometer was calibrated with a source of $Cs^{137}-Ba^{137m}$ using the conversion line of the 663-kev gamma-ray for calibration.

The momentum distribution of the electrons from a fission product source is shown in Fig. 1. Measurements were begun one hour after final separation of Pr^{143} from the Ce^{143} source and required about three hours. In addition to the Ce^{141} and Ce^{144} initially present, the source contained Pr^{143} which grew in over this four hour period. This nuclide did not contribute electrons with energies above 0.92 Mev, its maximum energy.[14] An internal conversion line corresponding to K conversion of a gamma-ray of energy 0.289±0.005 Mev is seen superimposed on the beta-spectrum. Figure 2 shows the Fermi plot of the Ce^{143} analyzed into three components. The maximum energies are 1.390±0.005, 1.090±0.005, and 0.710±0.010 Mev. Assuming straight line Fermi plots, the intensities of the 1.39-, the 1.09-, and the 0.71-Mev beta-groups are in the ratio 1.0:1.33:1.0. The values of F, the Fermi function, were taken from the graphs of Moszkowski.[15] In addition to the three beta-groups found, there was evidence of a fourth group of somewhat lower energy. This could not be resolved due to the presence of Ce^{141} and Pr^{143}, which had grown in, and to conversion lines. Its intensity appeared to be less than the intensities of the 0.71- or 1.39-Mev beta-groups. With the assumption that the three beta-ray groups found represent nearly all of the beta-transitions, the log ft values for the 1.39-, and 1.09-, and the 0.71-Mev betas are 7.75, 7.2, and 6.7, respectively. If the fourth group could have been resolved, and its intensity computed, it is not expected that the above values of log ft for the three higher energy beta-rays would be changed by very much. The 1.39-Mev beta and probably the 1.09-Mev beta have linear Fermi plots. Because of the pile-up of errors after two subtractions, plus the presence of Ce^{141} and the conversion contributions, it is not possible to make a statement regarding the shape of the 0.71-Mev component.

III. GAMMA-SPECTRA

Gamma-ray measurements were made from both $Ce^{142}(n,\gamma)$ sources and from fission product sources. Figure 3 shows the electron spectrum from a 1-mil uranium radiator with a fission product Ce^{143} source and with the spectrometer set to ~2.8 percent resolution. The Ce^{143} beta-rays were absorbed out with a copper absorber placed between the source and uranium radiator. As in all measurements of photoelectrons ejected from uranium radiators, the source was left in the spectrometer for three days to check on the decay of the photopeaks. In Fig. 3 the photopeaks correspond to gamma-rays of 0.289±0.005, 0.356±0.005, 0.660 ±0.010, and 0.720±0.010 Mev. The spectrometer was calibrated with the 0.663-Mev gamma of $Cs^{137}-Ba^{137m}$.[16]

In addition to the gamma-ray measurements made with the lens spectrometer, some measurements were also carried out with a scintillation spectrometer. The instrument consisted of a sodium iodide crystal, an RCA 7140A photomultiplier tube used in conjunction with a ten-channel pulse analyzer. With this instrument it was possible to measure x-rays and gamma-rays of energies below those measurable with the beta-ray spectrometer, but with much poorer resolution (~20 percent). The scintillation spectrometer was calibrated in appropriate energy regions with the 0.057-Mev[17] x-rays of Ta^{181}, the 0.320-Mev[18] gamma-ray of Cr^{51}, the 0.4112-Mev[19] gamma-ray of Au^{198}, and the 0.663-Mev gamma-ray of $Cs^{137}-Ba^{137m}$. Measurements were made on Ce^{143} from both fission product and (n,γ) sources

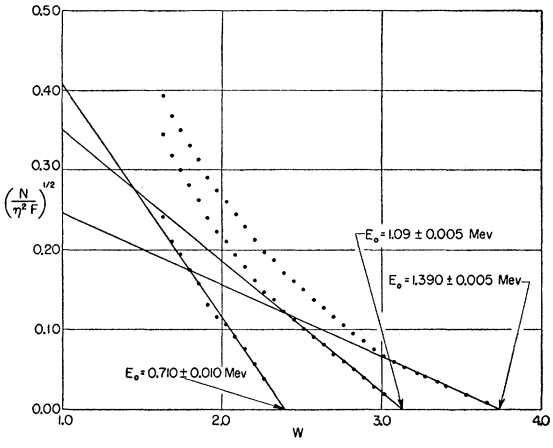

FIG. 2. Fermi plot of electron spectrum of Ce^{143}.

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[15] S. Moszkowski, University of Chicago, Institute for Nuclear Studies, Progress Report, August, 1948–September, 1949, Part IV (unpublished).
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[19] DuMond, Lind, and Watson, Phys. Rev. **73**, 1392 (1948).

and gamma-rays were observed at 0.0349±0.001, 0.126 ±0.005, 0.290±0.005, and 0.660±0.010 Mev. A typical gamma-ray spectrum as measured on the scintillation spectrometer is shown in Fig. 4. The 0.057-Mev gamma-ray reported by Kondaiah[6] and by Keller and Cork[5] and observed through its conversion electrons was not observed in the scintillation spectrum, and is apparently highly converted. Within experimental error, the 0.0349-Mev line corresponds to Pr K x-rays arising from internal conversion. With the poorer resolution of the scintillation spectrometer, the 0.356-Mev gamma-ray could not be resolved. It is estimated that it is approximately a factor of 5 less intense than the 0.290-Mev gamma-ray. Likewise the 0.720-Mev gamma-ray could not be seen. It appears from the lens spectrometer data to be of lower intensity than the 0.660-Mev line, although it is difficult to estimate their ratio. The intensity ratio of the 0.290-Mev gamma to the 0.660-Mev gamma is very roughly 4, in agreement with the estimate of Kondaiah.[6] The intensity ratio of the 0.290-Mev gamma to the 0.126-Mev gamma is very approximately 5.

Supplementing the gamma-ray measurements made with a single sodium iodide crystal, a few coincidence experiments were run utilizing two sodium iodide scintillators. In this way it was hoped to find lower intensity gamma-rays in coincidence with previously found gammas, but which had not been resolved above the high Compton backgrounds in the single crystal experiments. The coincidence circuit had a resolving time of 0.95×10^{-6} second. The circuit was gated by pulses from one crystal corresponding to a chosen energy interval, and coincidences registered between the first and second crystals were measured as a function of the energy of the coincident gammas counting in the second crystal. In these experiments the Ce^{143} samples were placed between the two sodium iodide crystals separated only by the thickness of the sample plus Lucite absorbers to remove betas (a few centimeters). When the coincidence circuit was gated with pulses from the

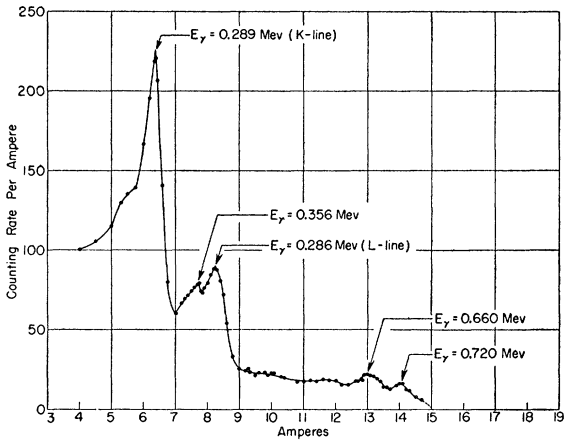

FIG. 3. Photoelectrons ejected from a 1-mil U radiator by gamma-rays of Ce^{143}.

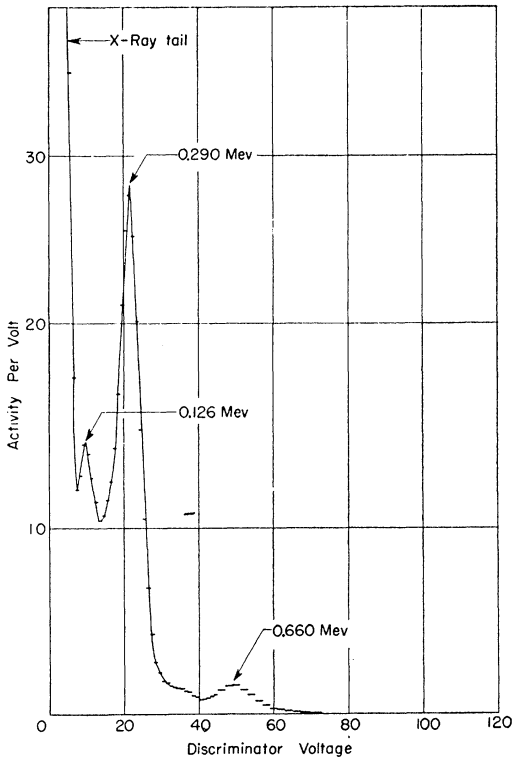

FIG. 4. Scintillation spectrum of gamma-rays of Ce^{143}.

first crystal corresponding to the energy interval 0.095 to 0.145 Mev, a coincident gamma-ray of ~0.160 Mev was found. The energies of the 0.160-Mev and the 0.126-Mev gamma-rays add to (within experimental error) the energy of the 0.290-Mev transition and apparently offer an alternative mode of decay from the 0.290-Mev level. In another similar experiment the 0.035-Mev line was found in coincidence with the 0.356-Mev gamma ray, and probably with the 0.290-Mev gamma-ray. As both gamma-rays are partially internally converted this result might be expected, assuming the decay scheme proposed below.

IV. PROPOSED DECAY SCHEME FOR Ce^{143}

Figure 5 gives a proposed decay scheme for Ce^{143}. The log ft values for the 1.39- and 1.09-Mev beta-groups are 7.75 and 7.2, respectively, placing these beta-transitions in the first-forbidden group.[20] The log ft value of 6.7 for the 0.71-Mev beta-group seems too high for an allowed transition but is consistent for a transition where $\Delta I=1$, No, $\Delta l=2$(l-forbidden) thus the choice $f_{7/2}\rightarrow h_{9/2}$. This leaves the question of the place of a fourth beta-group in the decay scheme. Were the fourth beta-group to feed directly the level lying only 0.057 Mev above what is proposed as the $h_{9/2}$ level of Pr^{143}, it is possible that the two beta-groups were not resolved. If the higher of the two Pr^{143} levels were

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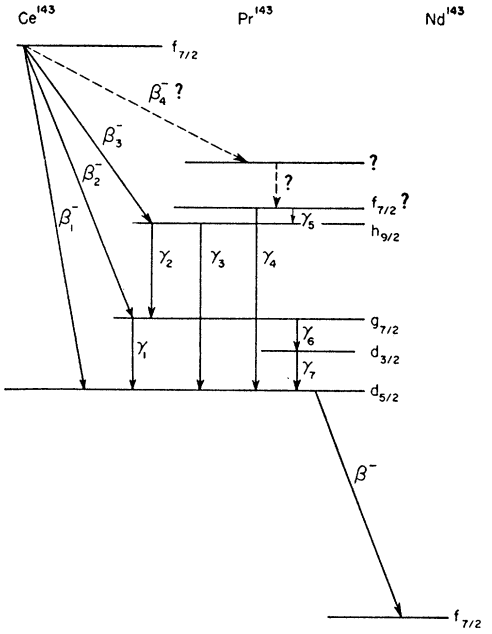

FIG. 5. Proposed decay scheme of Ce^{143}: $\beta_1^-=1.39^5$ Mev; $\beta_2^-=1.09^0$ Mev; $\beta_3^-=0.71$ Mev; $\gamma_1=0.290$ Mev; $\gamma_2=0.360$ Mev; $\gamma_3=0.660$ Mev; $\gamma_4=0.720$ Mev; $\gamma_5=0.057$ Mev; $\gamma_6=0.126$ Mev; $\gamma_7=\sim 0.160$ Mev.

assigned to $f_{7/2}$, then the beta-ray feeding that level should be an allowed transition on the basis of the assignment of $f_{7/2}$ for the Ce^{143}. Such a transition should produce a beta-group of greater intensity than any of the others. Because the 0.71-Mev group is less intense than the 1.09-Mev group, it seems likely that it is not an unresolved combination of the allowed and forbidden transitions. The assignment $f_{7/2}$ as shown in Fig. 5 is therefore questionable. It also seems unlikely that this level is $f_{7/2}$ because the K/L conversion ratio of the 0.057-Mev gamma as measured by Keller and Cork is less than unity, suggesting an $E2$ (or higher) transition.[21] If the 0.057-Mev transition were an $f_{7/2}\rightarrow h_{9/2}$ ($M1$) the K/L conversion ratio should be much greater than unity.[21] Perhaps the 0.057-Mev gamma-ray is in cascade with an undiscovered gamma which in turn is fed by the fourth lower energy beta-ray group. A more careful examination of the low energy end of the beta-spectrum of Ce^{143} is required to determine the place of a lower energy beta-group in the decay scheme and a more clear picture of the upper-lying levels of Pr^{143}. This must involve obtaining samples of Ce^{143} without serious contamination by Ce^{141}. A further possibility, of course, is that the assignment $h_{9/2}$ is also incorrect and β_3^- may be simply a first-forbidden transition.

The K/L conversion ratio of the 0.290-Mev gamma is approximately[5] 10, and the assignment $g_{7/2}\rightarrow d_{5/2}$ is consistent with this measurement. From our coincidence experiments we cannot, of course, say whether the 0.126-Mev gamma lies above or below the 0.160-Mev gamma in the decay scheme.

The assistance of L. M. Langer and M. Bunker with the β-spectrometer measurements and of J. W. Starner with the scintillation experiments is gratefully acknowledged.

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The Parallel Susceptibility of an Antiferromagnet at Low Temperatures*

JACK R. TESSMAN†
Department of Physics, University of California, Berkeley, California
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The spin wave method of Heller and Kramers is applied to a cubic antiferromagnetic crystal, oriented so that the direction of alignment of the sublattice spins is parallel to an external magnetic field. Taking into account exchange interactions and an anisotropy term, then the parallel susceptibility $\chi_{\parallel}$ is zero at $T=0°$K, in agreement with the result of the molecular field treatment of the problem by Van Vleck. If nearest neighbor magnetic dipole interactions are included, $\chi_{\parallel}$ is nonzero but negligibly small: $\chi_{\parallel}\sim 10^{-11}$ at $T=0°$K. For $T>0$ but much less than the antiferromagnetic Curie temperature, if the dipole interactions are neglected and the anisotropy is small, such that $\zeta=S(24JK)^{\frac{1}{2}}/kT\ll 1$, where K is an anisotropy constant, then $\chi_{\parallel}\propto T^2$. If $\zeta\gg 1$, then $\chi_{\parallel}\propto T^{\frac{1}{2}}\exp[-S(24JK)^{\frac{1}{2}}/kT]$.

1. INTRODUCTION

AN antiferromagnetic crystal does not exhibit any net spontaneous magnetization in the absence of an external magnetic field, because the magnetizations of the ordered sublattices, below the antiferromagnetic Curie temperature, are equal and opposite. In an external field, the magnetization of a two-sublattice antiferromagnetic crystal depends upon the orientation of the external field **H** with respect to the directions of alignment $\pm\mathbf{e}$ of the sublattice spins.

Using the modification of the Bloch spin wave method due to Heller and Kramers,[1] Hulthén[2] investigated the

* This work was assisted in part by the ONR.
† Now at Department of Physics, Pennsylvania State College, State College, Pennsylvania.

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