Atomic mass difference between ^{135}Ce and ^{135}La

T. Saito,* T. Toriyama, M. Kanbe, and K. Hisatake
Department of Applied Physics, Tokyo Institute of Technology, Ohokayama, Meguro-ku, Tokyo, Japan
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Electron capture decay of ^{135}Ce (17.6 h) has been used to determine the mass difference between ^{135}Ce and ^{135}La. The main component of the positrons (0.36%/decay) was found to feed the 300 keV level in ^{135}La with triple coincidences between two annihilation radiations and γ rays. The end-point energy of the β^+ main component was determined to be 694 ± 13 keV. Thus the mass difference between ^{135}Ce and ^{135}La is determined to be 2016 ± 13 keV. No anomaly is found for the EC/β^+ ratio.

[RADIOACTIVITY ^{135}Ce [from ^{139}La $(p,5n)$]; measured E_β, $\gamma\gamma^\pm\gamma^\pm$ coin; deduced Q. Magnetic spectrometer, Ge(Li) and NaI(Tl) detectors.]

I. INTRODUCTION

The atomic mass difference between ^{135}Ce and ^{135}La can be determined by measuring the Q value of electron capture of ^{135}Ce (17.6 h) decaying to ^{135}La. No measurement of the Q value has been reported yet, although Wapstra and Bos[1] estimated the Q value to be 2120 ± 100 keV. The maximum energy of the positrons from ^{135}Ce was reported to be $E_{\beta^+} \approx 400$ keV or $E_{\beta^+} = 810$ keV in older work,[2] but no reliable measurement has been published yet.

In this study we have measured the positron spectrum from ^{135}Ce with an iron-free β spectrometer, and also determined how the positrons feed levels in ^{135}La with triple coincidences between two annihilation radiations and γ rays. The preliminary work of the present study was already reported[3,4] in 1976 and another published work can be seen in Ref. 5.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Source preparation

The ^{135}Ce sources were made by ^{139}La$(p,5n)^{135}$Ce at the FM cyclotron of the Institute for Nuclear Study (INS), University of Tokyo. The bombarding energy was set at 43 MeV to get a high yield of ^{135}Ce and a low yield of ^{134}Ce. The procedures for chemical separation and for β source preparation were similar to those of Takahashi *et al.*[6] and Nagai and Hisatake,[7] respectively.

B. Positron spectrum

The β^+ spectrum of ^{135}Ce was measured with the INS iron-free $\pi\sqrt{2}$ β spectrometer.[8] The momentum resolution and solid angle were set at 1% and 1.2%, respectively. The source was mounted on a 2.5 μm thick Ni foil by electroplating.[7] A Si(Li) detector of 30 mm in diameter and 2 mm in thickness was used for detection of focused positrons.

Figure 1 shows the measured β^+ spectrum of ^{135}Ce mixed with that from the chain decay of ^{134}Ce (72 h) → ^{134}La (6.7 min) → ^{134}Ba after correcting for decays, detector efficiencies, and backgrounds. The $B\rho$ value written in the abscissa was calibrated with several conversion peaks of ^{135}Ce by use of the values of Nagai and Hisatake.[7] The β^+ spectrum of ^{134}La between 200 and 700 keV

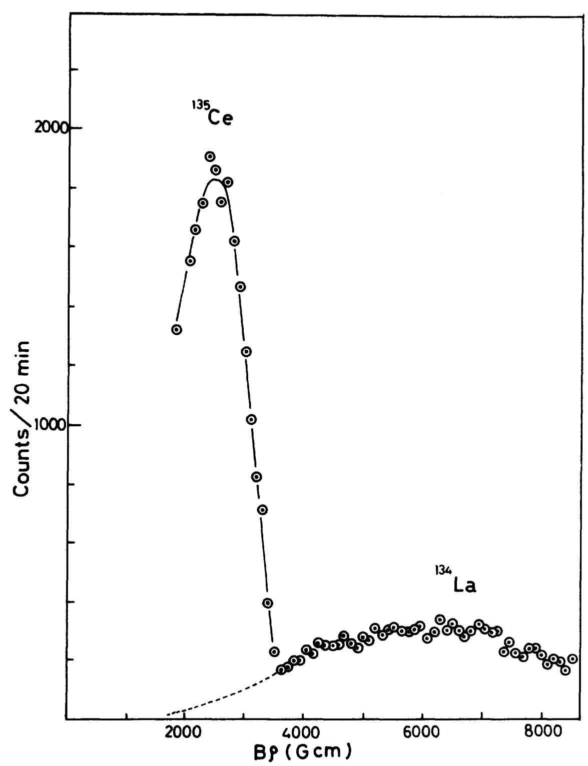

FIG. 1. Positron spectrum of ^{135}Ce mixed with that of ^{134}La. The dashed curve is the intensity for ^{134}La estimated from the Kurie plot analysis.

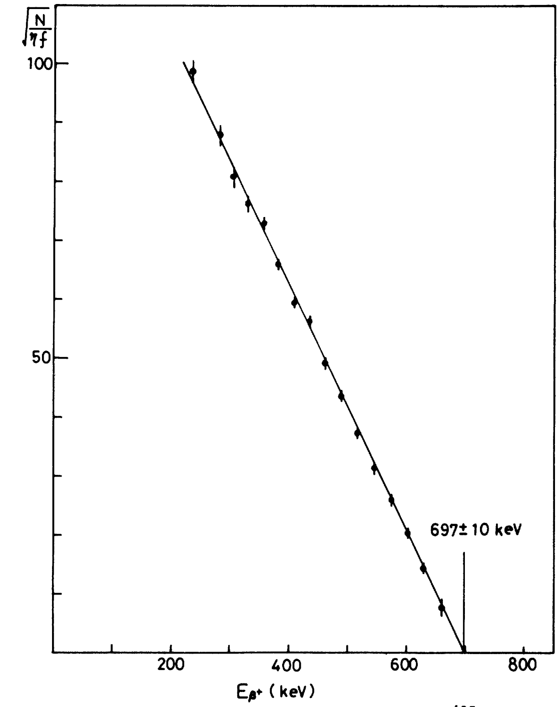

FIG. 2. Kurie plot of positrons from ^{135}Ce.

was determined from the Kurie plots of two β^+ components of ^{134}La, referring to those of Julian and Jha.[9] The β^+ spectrum of ^{134}La thus estimated is indicated in Fig. 1 by a dashed curve.

Figure 2 shows the Kurie plot of the β^+ spectrum of ^{135}Ce. From the least squares analysis of 12 points from the highest energy, the end-point energy was determined to be

$$E_{\beta^+}\,(^{135}\mathrm{Ce}) = 697 \pm 10\ \mathrm{keV}\,.$$

The present result is in agreement with the unpublished data[5] of $E_{\beta^+} = 705 \pm 3$ keV.

C. Triple coincidences between two annihilation radiations and γ rays

Two annihilation radiations and γ rays from ^{135}Ce were detected with a 12.7 cm (diameter) × 10.5 cm NaI(Tl), a 11.4 cm (diameter) × 10.5 cm NaI(Tl),

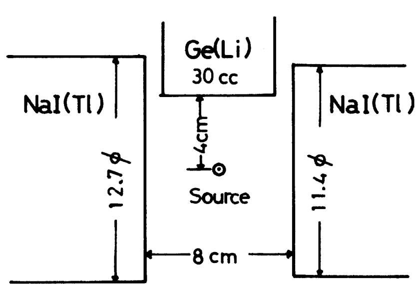

FIG. 3. Arrangement of triple coincidences between two annihilation radiations and γ rays.

and a 30 cm^3 Ge(Li) detector; the arrangement is schematically shown in Fig. 3. The γ-ray sources were put in a plastic cylinder, whose wall thickness was 2.5 mm, to stop all the positrons from ^{135}Ce. A conventional fast-slow coincidence system was used. The overall resolving time was $2\,\tau = 100$ nsec.

The gate positions of the two NaI(Tl) detectors were set at 511 ± 88 keV, considering the energy resolutions (about 10%) of the NaI(Tl) detectors. Triple coincidences were carried out in three runs whose counting times were 12, 10, and 10 h, respectively, to adjust source intensities below 2500 counts/sec for the Ge(Li) detector. The coincidence spectrum of the first run is shown in Fig. 4 together with the partial decay scheme.[2] Peaks can be seen at 119, 206, 265, 300, and 380 keV. Since the above energy gates were as broad as 88 keV, many three γ-ray cascades were involved in the $\gamma\gamma\gamma$ triple coincidences. We estimated these real triple coincidence intensities based on the decay scheme[2]; in the estimation, the detection efficiency of the present system was considered for all γ rays from 380 to 1100 keV. Table I shows both experimental triple coincidence intensities and estimated real $\gamma\gamma\gamma$ intensities. In the table the estimated $\gamma\gamma\gamma$ intensity is normalized to the experimental one for the 206 keV peak,

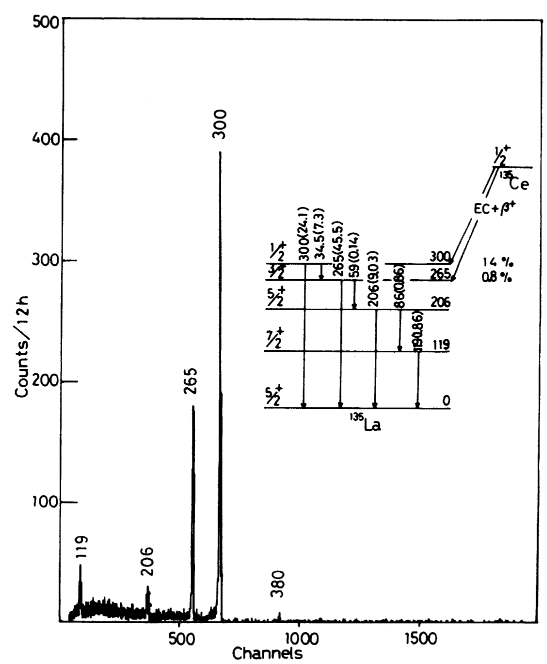

FIG. 4. Triple coincidence spectrum of the first run. The gate positions of two NaI(Tl) detectors were set at 511 ± 88 keV. The partial decay scheme inserted is taken from Ref. 2, where numbers in parentheses are transition intensities in 100 decays.

TABLE I. Relative triple coincidence intensity with two annihilation radiations.

E_γ (keV)	Coincidence intensity[a]	Estimated $\gamma\gamma\gamma$ intensity[b]	Net $\gamma^{\pm}\gamma^{\pm}\gamma$ intensity	Final $\gamma^{\pm}\gamma^{\pm}\gamma$ intensity
119[c]	39.5 ± 5.0	43.8 ± 8.8	-4.3 ± 10.1	<0.01
206	33.2 ± 6.5	32.3 ± 6.5	0.9 ± 9.2	<0.01
265	403 ± 15	44.2 ± 8.8	359 ± 17	0.36 ± 0.02
300	1000 ± 24	10.7 ± 2.1	989 ± 24	1.00 ± 0.03
379	22.0 ± 5.0	18.0 ± 3.6	4.0 ± 6.2	<0.01

[a] Triple coincidence counts for three runs corrected for the detector efficiency of the Ge(Li) detector. The intensity for the 300 keV peak is normalized as 1000.
[b] The estimated $\gamma\gamma\gamma$ intensity is normalized to the experimental one for the 206 keV peak; the net $\gamma^{\pm}\gamma^{\pm}\gamma$ intensity, 0.9, is estimated from the decay scheme (Ref. 2). The error for the estimation is assumed to be 20% for each peak.
[c] Both the 119.5 keV and the 118.1 keV γ rays are included.

where the contribution from β^+ decays is estimated to be negligibly small. As seen in Table I, the final triple coincidence intensity with two annihilation radiations was found to be negligibly small for the 119 and 379 keV γ rays, as is expected from the decay scheme. Thus the procedure for correction of real triple coincidences is confirmed. The final relative triple coincidence intensities with two annihilation radiations are shown in the last column in Table I.

The total intensity of positrons was obtained from the intensity ratio of the 518 to 511 keV peaks in the single spectrum taken with a Ge(Li) detector. Since the present source also contained ^{134}Ce, we carefully selected only the 17 h component of the 511 keV peak. Using the intensity ratio $I_\gamma(518)/I_\gamma(511) = 17.7 \pm 1.8$ and the evaluated intensity of the 518 keV transition, 13.7%/decay, the total β^+ intensity of ^{135}Ce was determined to be

$$I_{\beta^+}(^{135}\text{Ce}) = 0.38 \pm 0.05\%/\text{decay}\,.$$

By combining this value with the relative coincidence intensity shown in Table I, the β^+ branching ratio can be deduced for the 265 and 300 keV levels in ^{135}La. In this deduction the branching ratio of the 300 keV level was taken from the decay scheme[2]; the partial decay scheme is shown in the insert of Fig. 4. Since no error for the branching ratio is given in the decay scheme, we tried to estimate the error from the data compiled in the Nuclear Data Sheet[2] as follows: Most of the error is originated from the intensity of the 34.5 keV transition. From the γ intensity and the $E2/M1$ mixing ratio we obtained $8.7 \pm 0.4\%$/decay for the 34.5 keV transition using the theoretical conversion coefficient of Hager and Seltzer,[10] although the decay scheme gives 7.3%. Since all of the present analysis has been based on the decay scheme, we assume the intensity of the 34.5 keV transition to be $7.3^{+1.8}_{-0.4}\%$ for the deduction of the β^+ branching ratio. The intensity of the 300 keV transition was obtained to be $24.1 \pm 0.8\%$ by a similar procedure; this value is just in agreement with that of the decay scheme. Table II shows the β^+ branching ratio obtained by use of these values.

D. Q value determination

Since positrons of ^{135}Ce were found to have two components, the Kurie plot analysis should be made separately for each component. From the Kurie plot for the component feeding to the 300 keV level, the end-point energy of the positrons was determined to be

$$E_{\beta^+}\ (\text{to 300 keV level}) = 694 \pm 13\ \text{keV}\,,$$

which is also shown in Table II.

Thus the Q value of the electron capture of ^{135}Ce to the ground state of ^{135}La is determined to be

$$Q_{EC}(^{135}\text{Ce}) = 2016 \pm 13\ \text{keV}\,,$$

which is compared with the estimated value of Wapstra and Bos,[1] 2120 ± 100 keV.

III. DISCUSSIONS AND CONCLUSIONS

A. Electron capture to positron ratio

As a byproduct, the EC/β^+ ratio for the 300 keV level can be found to be 38 ± 7 by use of the (EC $+\beta^+$) branching ratio,[2] 14%. The theoretical value interpolated from the table of Gove and Martin[11] is 52 ± 4. If one considers the possible error of

TABLE II. β^+ branching ratio and end-point energy.

Level (keV)	β^+ branching (%/decay)	E_{β^+} (keV)
265	$0.019^{+0.008}_{-0.019}$	
300	$0.36^{+0.07}_{-0.05}$	694 ± 13

the theoretical calculation, these values are in reasonable agreement; the anomaly reported by Firestone *et al.*[12] is not found for this transition.

B. Q value determination

The Q value of electron capture of ^{135}Ce has been determined with the combination of conventional β^+ spectroscopy and triple coincidences. The main source of the errors is statistical errors due to weak branching of positrons. Judging from the present branching ratio, 0.4%/decay, and the final error of 13 keV, this method can be extended to EC nuclides of 0.1% β^+/decay. If one uses stronger sources and higher transmission spectrometers, this limit would be lowered. Since there are many such nuclides whose Q values have not been established in the Table of Isotopes,[13] this kind of experiment should be encouraged.

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*Present address: Shimizu Construction Company Ltd., Kyōbashi, Chūō-ku, Tokyo, Japan.

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