NUCLEAR MATRIX ELEMENTS IN BETA DECAY OF La^{140}

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The circular polarization of 1.6-MeV γ rays accompanying the β decay of La^{140} with 2.2-MeV end-point energy is measured. Conclusions are drawn regarding the magnitudes of the nuclear matrix elements and the cause of the large log ft value of the La$^{140} \rightarrow$ Ce^{140} transition between 3$^-$ and 2$^+$ states.

1. INTRODUCTION

BETA decay in La^{140} with end point $E_0 = 2.2$ MeV is first-forbidden. However, log ft = 9.1 somewhat exceeds the typical value (7—8) for most nonunique once-forbidden β decays. In addition, there is no basis for assuming that the given transition is unique, since it has been established reliably that La^{140} has spin 3,[1] and the first excited state of the even-even nucleus Ce^{140} resulting from β decay is of 2$^+$ character. The large log ft value therefore obviously is an indication that the nuclear matrix elements have unusual values.

In 3$^- \rightarrow$ 2$^+$ β transitions the principal role is played by the nuclear matrix elements $\int \mathbf{r}$, $\int i\boldsymbol{\sigma} \times \mathbf{r}$, $\int i\alpha$, and $\int B_{ij}$ ($\int B_{ij}$ is a second-rank tensor matrix element). In the case of once-forbidden non-Coulomb β transitions these matrix elements can be determined experimentally from four independent experiments,[2] by measuring: 1) the deviation from the allowed β spectrum shape, i.e., the correction factor C(W); 2) the asymmetry coefficient E(W) in β-γ directional correlations; 3) the angular β-polarized γ correlation $\omega(W, \theta)$; 4) log ft. Similar experiments have been performed to investigate analogous β transitions in Sb^{124}[3-5] and Eu^{152}.[5-7]

In the present work we have measured the angular correlation $\omega(W, \theta)$ for La^{140} between 1.6-MeV circularly polarized γ rays and electrons with 2.2-MeV end point. This experiment in conjunction with the experimentally determined correction factor C(W)[5] and the asymmetry coefficient E in β-γ directional correlations[8] permits certain conclusions regarding the magnitude of the nuclear matrix elements.

2. MEASUREMENT OF THE CIRCULAR POLARIZATION OF GAMMA RAYS

The experimental procedure resembled that employed in our earlier work[9] with the addition of an automatic measuring procedure. An automatic switching circuit performed the following periodically repeated operations: setting of the measurement time t_m for a given magnetic field direction in the scatterer, reversal of the current direction in the magnet coil, and switching-off of one group and switching-on of other groups of coincidence-registering scalers. The scaler readings for a given magnetic field direction in the scatterer were totaled. The time of a single coincidence measurement was $t_m = 20.5$ sec.

Details of the automatic equipment and its operation have been described in [10]. Automatization of the measurements greatly reduced the effect of slow drift on the counts and simplified the measuring process, which has been especially difficult for La^{140} because of its relatively short half-life ($T_{1/2} = 40.3$ hr).

We measured the coincidences of scattered γ radiation having 1600 keV initial energy and β electrons having energies W = 3.9—5.3 $m_0 c^2$. The resolving time of the coincidence circuit was $\tau = 3 \times 10^{-8}$ sec. The mean γ-scattering angle was $\bar{\vartheta} = 50°$ and the mean angle between γ and β rays was $\bar{\theta} = 160°$.

Since the investigated β decay comprises only 10% of the total number of decays and only a small fraction of the β energy spectrum was used, it was necessary to increase the efficiency of β-γ coincidence selection. For this purpose the crystal of the scintillation γ spectrometer was sur-

rounded with a 3-mm lead absorber that stopped most relatively soft γ rays while transmitting ~ 90% of the γ rays representing single scattering in iron at a given angle. The effect of the shield is shown in Fig. 1, which represents the spectrum of scattered γ rays from the Co^{60} source without a lead absorber (curve 1) and with the 3-mm lead absorber (curve 2). Increased thickness of the lead shield had practically no effect on the spectrum shape. It was thus possible to discriminate a considerably larger portion of the γ spectrum and to increase the coincidence counting rate. The mean counting rate of true β-γ coincidences in our measurements on La^{140} was ~ 0.5 coincidences/sec.
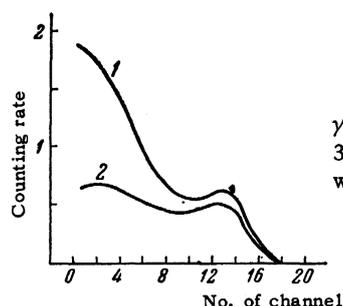

FIG. 1. Spectrum of scattered γ rays from Co^{60} source with 3-mm lead absorber (curve 2) and without absorber (curve 1).

The La^{140} source of 8-mm diameter was prepared by evaporation onto cigarette paper. The thickness of the deposit was 10—15 mg/cm^2. The source was replaced every 2.5 days.

The measured effect ϵ, defined as in [9], was $\epsilon = -0.90 \pm 0.53\%$. The value of ϵ was used to calculate $\omega(\overline{W}, \overline{\theta})$ from the formula[11]

$$\varepsilon = 2f\omega\,(\overline{W},\,\overline{\theta})\,\overline{(v/c)\cos\theta d\sigma_c/d\sigma_0}$$

The mean values $\overline{W}$ and $(\overline{v}/c)$ were determined from the experimental spectrum shape:[5] $\overline{W}$ = 4.2 and $(\overline{v}/c) = 0.97$. The quantity $\cos\theta \cdot d\sigma_c / d\sigma_0$ was averaged graphically as described in [11], yielding

$$\overline{|\cos\theta \cdot d\sigma_c/d\sigma_0|} = 0.39.$$

We thus obtained

$$\omega\,(\overline{W} = 4.2;\ \overline{\theta} = 160°) = 0.15 \pm 0.09.$$

In treating the result we disregarded the effect of the partial β spectrum with the end point W_0 = 4.3, a part of which contributed to β-γ coincidences. This is entirely justified, since an estimate based on the β-spectrum shape in [5] showed that the β spectrum with W_0 = 4.3 contributes only ~ 5% to the energy region W = 3.9—5.3.

3. DISCUSSION OF EXPERIMENTAL DATA

It must first be mentioned that both Rudakov's measurements[8] of the asymmetry coefficient E in β-γ directional correlation and our measurements of γ circular polarization disagreed with the effects predicted for unique β decay. This was confirmed by the direct measurement of La^{140} spin (I = 3).[1]

As already indicated, the value of ω together with the experimental values of E and the correction factor C enable us, at least in principle, to determine the nuclear matrix elements governing the investigated β decay in La^{140}. Following Kotani's notation,[2] we introduce the nuclear parameters x, u, and Y which express the nuclear matrix elements in units of the matrix element $\int B_{ij}$:*

$$\eta u = C_A \int i\,[\sigma r],$$
$$\eta Y = -C_V \int i\alpha - \xi\left(C_A \int i\,[\sigma r] - C_V \int r\right),$$
$$\eta x = -C_V \int r, \quad \eta = C_A \int B_{ij},$$

with the Coulomb factor $\xi = \alpha Z/2R$. To determine the nuclear parameters we then have[2] a system of three independent equations:

$$C = f_1\,(x, u, Y, W), \tag{1}$$
$$\omega = f_2\,(x, u, Y, W, \theta), \tag{2}$$
$$E = f_3\,(x, u, Y, W), \tag{3}$$

where W is the electron energy and θ is the angle between the electron and the γ ray. The functions in (1)—(3) are quadratic in the unknowns x, u, and Y. We substitute the mean experimental electron energy and the angles from the measurement of γ circular polarization; we thus obtain three numerical equations whose left-hand sides are the experimentally determined quantities

$$C = 2.2 \pm 0.4,$$
$$\omega = 0.15 \pm 0.09, \qquad E = 0.078 \pm 0.023. \tag{4}$$

The correction factor was here calculated for electron energy $\overline{W}$ = 4.2 from the expression C(W) = $q^2 + 0.85p^2 + 10 \pm 5$ given in [5]. The value of E was obtained from [8] for electrons with W = 4.5 by converting the angular dependence into an expansion in Legendre polynomials.

In solving the system of equations we eliminated from (1) and (2) the parameter Y, which was determined explicitly from (3). This left two equations (1') and (2') in the unknowns x and u, which were solved graphically. Figure 2 shows the functional relations between u and x given by
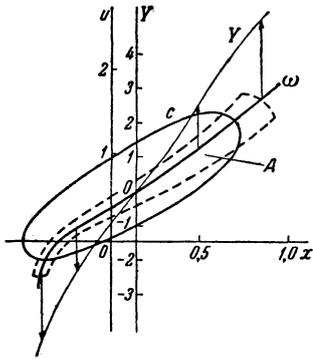
*$[\sigma r] = \sigma \times r$

FIG. 2. The nuclear parameters x, u, and Y. The solid curves C and ω represent the mean experimental quantities in (4) of the text. The region A bounded by dashed lines includes the values allowed for x and u with experimental errors taken into account. The parameter Y was constructed on the ω curve.

(1') (curve C) and (2') (curve ω) for the mean experimental values (4). The intersections of these curves determined the nuclear parameters x and u and the corresponding values of Y, thus solving the original system (1)—(3). In this way we obtained two sets of nuclear parameters:

$$x = +0.7, \quad u = +1.4, \quad Y = +2.3, \quad \text{(I)}$$
$$x = -0.35, \quad u = -0.20, \quad Y = -1.64, \quad \text{(II)}$$

which differ in the sign of the ratio between the first-rank nuclear matrix elements and the matrix element $\int B_{ij}$.

We introduce the absolute values of the nuclear matrix elements corresponding to set I:

$$\left| \int B_{ij} \right| / R = (5.1 \pm 0.26) \cdot 10^{-2}, \qquad \left| \int r \right| / R = 4.5 \cdot 10^{-2},$$
$$\left| \int i [\sigma r] \right| / R = 7.25 \cdot 10^{-2}, \qquad \left| \int i \alpha \right| = 3.1 \cdot 10^{-2},$$

where R is the nuclear radius in units of the electron Compton wavelength. The matrix element $\int B_{ij}$ was calculated[2] from the value of log ft and the correction factor C(W). According to solutions I and II, in the β decay of La[140] the first-rank nuclear matrix elements are of the same order of magnitude as the second-rank matrix element $\int B_{ij}$.

As mentioned at the beginning of this article, there are β decays of Sb[124] and Eu[152] which are 3⁻ → 2⁺ transitions; these, like the β decay of La[140], differ from other once-forbidden β decays by a large log ft value. Experimental calculations of the nuclear matrix elements in these β transitions[3,4,6] indicate the existence of forbiddennesses, as a result of which the first-rank matrix elements $\int r$ and $\int i\sigma \times r$ are small compared with $\int B_{ij}$. In the shell model additional forbiddennesses can be associated with a change of j for an individual nucleon in a deformed nucleus with a changed value of K. There is no basis for assuming similar rules of forbiddenness in La[140]. On the shell model La[140] has one $f_{7/2}$ neutron in addition to the filled shells and one $g_{7/2}$ proton hole; j forbiddenness should therefore not

exist. Moreover, nuclear deformation cannot be expected near closed shells.

We have now determined the nuclear matrix elements for the β decay of La[140] from the mean experimental values of C, ω, and E known with the respective accuracies $\pm \Delta C$, $\pm \Delta \omega$, and $\pm \Delta E$. When the experimental errors affecting all three quantities are taken into account we obtain the region of allowed values of x and u bounded by the dashed curve in Fig. 2. The same figure shows the magnitude of the nuclear parameter Y, which is equal to the straight-line segments parallel to the Y axis between the Y and ω curves, as illustrated at two points.

Figure 2 shows that the allowed region for x and u excludes the possibility that their values are simultaneously small: if one of the nuclear matrix elements $\int r$ or $\int i\sigma \times r$ vanishes, the other will be comparable to $\int B_{ij}$. Thus our experimental results together with other data prove that the large value of log ft in La[140] β decay cannot be attributed to the aforementioned forbiddenness rules. It is obviously associated with the cancellation effect[2] resulting from the matrix-element phase selection.

The approximation employed in[2] to deduce the formulas that we have used is inadequate for the present case. More accurate theoretical calculations are required for the exact determination of the nuclear matrix elements. This was not required in the foregoing analysis, since the experimental errors do not permit us to determine the absolute values of the matrix elements.

A more exact determination of the nuclear matrix elements for La[140] β decay requires a substantial reduction of the experimental errors. The mere refinement of the experiment described in the present work will only slightly change the allowed region of nuclear parameter values. To illustrate the effect of experimental errors, Fig. 3 shows the curves for C + ΔC and C − ΔC as well as for ω + Δω and ω − Δω at the maximum value of E + ΔE. The common region is shaded in the figure. The final results will be practically unaffected by prolonged measurements reducing the

FIG. 3. Determination of C and ω for maximum E when experimental errors are taken into account.
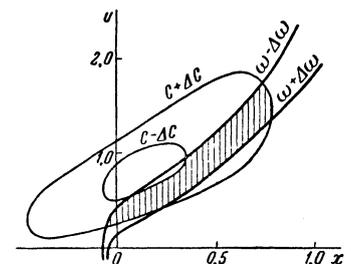
error in ω to about one-half. The reduction of the errors in C and E would be more significant.

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