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Investigation of the Nonunique First-Forbidden β Decay. II. Analysis of the $\frac{7}{2}^-$(0.581 MeV) $\frac{5}{2}^+$ β Transition in ^{141}Ce

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The β moments of the $\frac{7}{2}^-(\beta)\frac{5}{2}^+$ transition from the decay of ^{141}Ce, have been extracted from the experimental data. We have obtained the following results: $\langle i\vec{r}\rangle=0.98\pm0.20$ fm, $\langle\vec{\sigma}\times\vec{r}\rangle=-1.11\pm0.35$ fm, $\langle iB_{ij}\rangle=1.30\pm0.50$ fm, and $\langle i\vec{\alpha}\rangle/\xi=2.16\pm0.45$ fm. These results are consistent with the analysis of the $\frac{7}{2}^-(\beta)\frac{5}{2}^+$ transition in ^{139}Ba and with the measurement of the γ moment $\langle i\vec{r}\rangle$ from the isobaric analog state of the ground state in ^{141}Ce to the ground state in ^{141}Pr. We present here a discussion concerning the polarizability effects due to the charge-exchange excitation modes.

I. INTRODUCTION

In a previous paper[1] a detailed study of the 2^-(0.962 MeV)2^+ β transition from the decay of ^{198}Au has been carried out. Although that first-forbidden β transition is the best known one from the experimental point of view, it has not been possible to extract any information concerning charge-dependent excitation modes because of: (a) the validity of the ξ approximation and (b) the scanty information on the nuclear structure of the states involved in the process.

Here we have a more favorable case. In fact, the $\frac{7}{2}^-$(0.581 MeV)$\frac{5}{2}^+$ β transition from the decay of ^{141}Ce presents the following interesting features:
(i) The low-lying states in the ^{141}Ce and the ^{141}Pr nuclei are experimentally well known,[2] and many of their properties (magnetic-dipole moments, electric-quadrupole moments, $E2$ transitions, one-body transfer processes, etc.) are satisfactorily explained in the framework of the quasiparticle-plus-quadrupole-quadrupole phonon model.[3-6] In particular the ground states in ^{141}Ce and ^{141}Pr nuclei are in good approximation pure one-quasiparticle $2f_{7/2}$ and $2d_{5/2}$ states, respectively.
(ii) The experimental information on the β process[7,8] indicates that the ξ approximation is not valid. This fact is also supported by the single-particle estimate of the linear combination

$$Y=-\xi[\Lambda-1+(g_A/g_V)\Lambda_1], \tag{1}$$

where the quantities Λ and Λ_1 are

$$\Lambda=\frac{\langle\alpha\rangle}{\xi\langle i\vec{r}\rangle}, \tag{2}$$

$$\Lambda_1=-\frac{\langle\vec{\sigma}\times\vec{r}\rangle}{\langle i\vec{r}\rangle}, \tag{3}$$

and the remaining notation is the same as in Ref. 1. For the $2f_{7/2}\to 2p_{5/2}$ transition $\Lambda_1=1$; and using the Fujita-Eichler estimate[9,10] for the β moment $\langle\vec{\alpha}\rangle$ (see the next section) we have with $g_A=-1.19g_V$,

$Y \approx 0.2\xi = 2.65$ in natural units ($\hbar = m = c = 1$).

(iii) The matrix element $\langle i\vec{r}\rangle_\gamma$ of the $E1$ γ transition between the isobaric analog (IA) of the ground state in ^{141}Ce and the ground state of ^{141}Pr, which is related by rotational invariance in isospace to the transition matrix element $\langle i\vec{r}\rangle_\beta$, has been recently measured.

The result reported by Ejiri *et al.*[11] from the ^{140}Ce$(p,\gamma)^{141}$Pr reaction is

$$(2T_i)^{1/2}\langle i\vec{r}\rangle_\gamma = 0.65 \pm 0.16 \text{ fm}, \qquad (4)$$

while Shoda *et al.*[12] obtained the value

$$(2T_i)^{1/2}\langle i\vec{r}\rangle_\gamma = 0.66 \pm 0.05 \text{ fm}, \qquad (5)$$

on the basis of the ^{141}Pr$(e,e'p)^{140}$Ce reaction study. A level diagram for the relation between the $E1$ γ decay from the IA state and the β decay is shown in Fig. 1. The γ moment $\langle i\vec{r}\rangle_\gamma$ is reduced with respect to the pairing-model estimate by a factor of ≈ 4 and the hindrance has been attributed to the core-polarization effect induced by the charge-exchange dipole field.[13]

(iv) The β transition $\frac{7}{2}^-(2.223\text{ MeV})\frac{5}{2}^+$ from the decay of ^{139}Ba, which is similar to the corresponding β transition in ^{141}Ce (the wave functions of the initial and final states are similar), has been recently analyzed by Sunier and Berthier.[14] They have reported that a hindrance factor of ≈ 3.5 remains between the experimental and the calculated β moments.

In short, if the experimental data on the $\frac{7}{2}^- \to \frac{5}{2}^+$ β transition from the decay of ^{141}Ce are accurate enough, the deviation from the ξ approximation

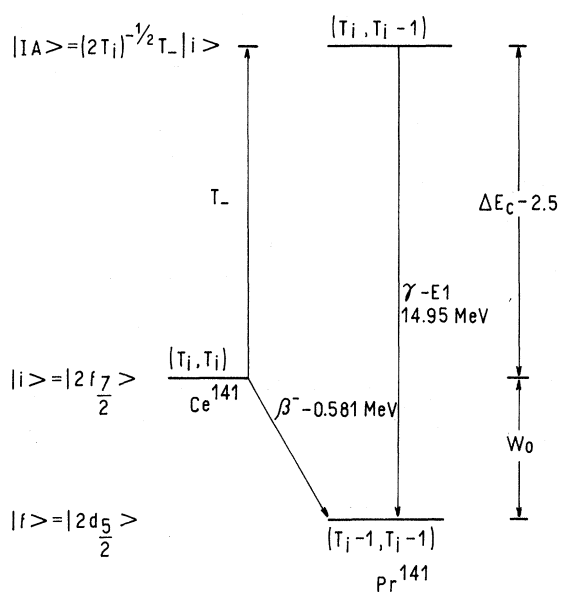

FIG. 1. Schematic diagram of β^- decay and the IA $E1$ γ process showing notation and energy relationships.

will allow the extraction of the β moments. This information, together with the above mentioned one on the IA state in ^{141}Pr and the β moments in ^{139}Ba will permit us to discuss:

(a) the core polarization effects associated with the isospin ($\tau = 1$) and spin ($\sigma = 1$) excitation modes,

(b) the purity of the IA state in ^{141}Pr, and

(c) the validity of the conserved vector current hypothesis.

II. RELEVANT THEORY

In the evaluation of the relativistic β moment $\langle\vec{\alpha}\rangle$ one may take advantage of the conserved vector current theory (CVC) which connects the β^- vector current $J_\mu^{(V)}$ and the electromagnetic current J_μ^{el} through the relation

$$J_\mu^{(v)} = -\frac{g_V}{e}[T_-, J_\mu^{\text{el}}], \qquad (6)$$

where T_- is the isospin lowering operator. By using the continuity equation for the current $J_\mu^{(V)}$, the following expression is easily obtained[9,10] for β^- decay

$$\langle\vec{\alpha}\rangle = (W_0 - 2.5 + \lambda_0\xi)\langle i\vec{r}\rangle, \qquad (7)$$

with

$$\lambda_0\xi = \langle[V_C, i\vec{r}]\rangle/\langle i\vec{r}\rangle, \qquad (8)$$

where $W_0 = W_i - W_f$ is the transition energy and V_C is the Coulomb potential.

Taking into account the Ahrens-Feenberg approximation[15] for the Coulomb term [$\lambda_0(\text{AF}) = 2.4$], Fujita[9] and Eichler[10] arrived at the result

$$\langle\vec{\alpha}\rangle/\langle i\vec{r}\rangle\xi = 2.4 + (W_0 - 2.5)\xi^{-1} = \Lambda(\text{FE}). \qquad (9)$$

The energy factor that appears in Eq. (7) can be related to the energy of the IA state $|\text{IA}\rangle$ of the initial state. In fact from the relation (6) it follows that the β matrix elements $\langle\vec{\alpha}\rangle$ and $\langle i\vec{r}\rangle$ for the transition $i \to f$, are related by isobaric symmetry to the corresponding matrix elements for the transition IA $\to f$. That is

$$\langle f|i\vec{r}_\beta|i\rangle = -\frac{g_V}{e}\langle f|[T_-, i\vec{r}_\gamma]|i\rangle$$

$$= \frac{g_V}{e}(2T_i)^{1/2}\langle f|i\vec{r}_\gamma|\text{IA}\rangle, \qquad (10)$$

on the assumption that $(T_3)_i = T_i$ and that $\langle f|T_A \sim 0$. A similar relationship is valid for the moments $\langle\vec{\alpha}\rangle_\beta$ and $\langle\vec{\alpha}\rangle_\gamma$. This means that

$$\left(\frac{\langle\vec{\alpha}\rangle}{\langle i\vec{r}\rangle}\right)_\beta = \left(\frac{\langle\vec{\alpha}\rangle}{\langle i\vec{r}\rangle}\right)_\gamma, \qquad (11)$$

and since the electromagnetic moments are connected by the continuity equation for the current

$J_\mu^{\rm el}$, the following expression is obtained[16]

$$(\langle\vec{\alpha}\rangle/\langle i\vec{r}\rangle)_\beta = E_\gamma = E_{\rm IA} - E_f = W_0 - 2.5 + \Delta E_C\,, \quad (12)$$

where $\Delta E_C = E_C(A, Z+1) - E_C(A, Z)$ is the Coulomb displacement energy. Considering the Coulomb potential of a uniformly charged sphere one gets $\Delta E_C = 2.4\xi$ and the above expression corresponds to the Fujita-Eichler approach. This is due to the fact that the Ahrens-Feenberg approximation is eqiuvalent to neglecting the effects of the Coulomb field in violating the isobaric relationship between the states i and IA.

Damgaard and Winther[17] have suggested that the matrix element of $[V_C, i\vec{r}]$ should actually be calculated by taking the Coulomb potential of a uniformly charged sphere, and they obtained that

$$\lambda_0({\rm DW}) = (3 - \epsilon_1)\,; \quad \epsilon_1 = \frac{\langle r^3\rangle}{r_0{}^2\langle r\rangle}\,. \quad (13)$$

Their formulation depends on the reliability of the nuclear wave functions. More strictly their approach means the expression (13) plus the evaluation of the ratio ϵ_1 without taking into consideration the effects of the core polarization induced by isospin-dependent interaction. In this way they arrived at the conclusion that the Fujita-Eichler approximation could be grossly in error [λ_0(DW) $\ll \lambda_0$(AF)] when the wave functions of the initial and final states differ in the number of radial nodes. The renormalization of the ratio ϵ_1, i.e., of the Coulomb-potential term, due to the $\tau = 1$ excitation mode has been recently calculated by Fayans and Khodel[18] in the framework of the finite Fermi-system theory. They concluded that even in the case of dealing with radial wave functions with different number of radial nodes, the Fujita-Eichler approach is valid up to 25%.

III. RESULTS

The available experimental information on the $\frac{7}{2}^- \to \frac{5}{2}^+$ β transition in ^{141}Ce nucleus is:

(a) The spectrum shape factor $C_\beta(W)$ measured by Beekhuis and Duinen[8] (see Fig. 2).

(b) The angular distribution of β rays from oriented nuclei

$$N_e(W, \theta) = 1 + N_1(W)\frac{p}{W} f_1 P_1 + N_2(W)\frac{p^2}{W} f_2 P_2\,. \quad (14)$$

The coefficients $N_1(W)$ and $N_2(W)$ contain information on the β moments according to

$$N_1(W) = -\frac{1}{\sqrt{2}}\, b_{11}^{(1)} - \frac{1}{\sqrt{6}}\, b_{12}^{(1)} + \frac{13}{18}\left(\frac{2}{5}\right)^{1/2} b_{22}^{(1)}\,,$$
$$N_2(W) = -\frac{7}{8}\left(\frac{2}{3}\right)^{1/2} b_{11}^{(2)} - \frac{7}{12}\left(\frac{5}{2}\right)^{1/2} b_{12}^{(2)} + \frac{\sqrt{7}}{12}\, b_{22}^{(2)}\,, \quad (15)$$

where $b_{LL'}^{(m)}$ are the particle parameters.[1] The experimental values obtained by Hoppes *et al.*[7] are indicated in Fig. 3.

(c) The partial half-life $t = 33$ days (cf. Ref. 2).

The matrix-element parameters used in the analysis are

$$\Lambda = \frac{\langle\vec{\alpha}\rangle}{\xi\langle i\vec{r}\rangle}\,,$$
$$\eta u = -g_A\langle\vec{\sigma}\times\vec{r}\rangle\,,$$
$$\eta z = g_A\langle iB_{ij}\rangle\,, \quad (16)$$
$$\eta = -g_V\langle i\vec{r}\rangle\,.$$

The formalism as well as the method of extraction of the β moments from the experimental data are given in Ref. 1. The χ^2 function is defined as

$$\chi^2 = \chi^2(C_\beta) + \chi^2(N_e)\,, \quad (17)$$

where $\chi^2(C_\beta)$ and $\chi^2(N_e)$ are the χ^2 functions for the spectrum shape factor and oriented nuclei (N_1 and

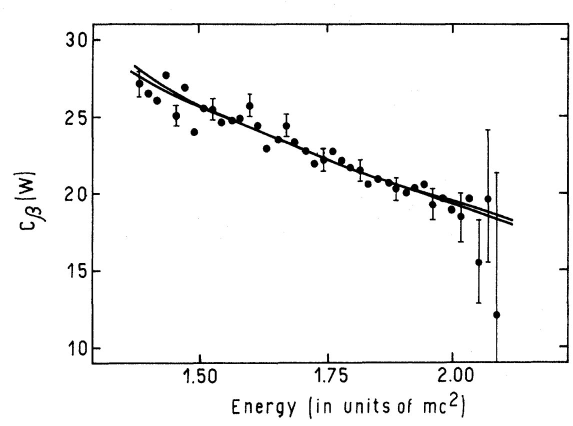

FIG. 2. Experimental shape-correction factor from Ref. 8, with theoretical values calculated from the β moments in the case A.

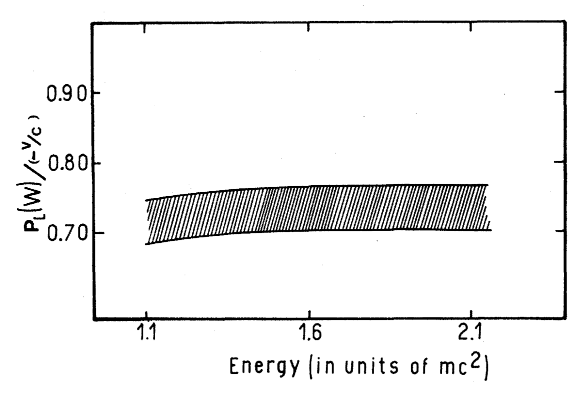

FIG. 3. Experimental results of the coefficients $N_1(W)$ and $N_2(W)$, with theoretical values derived from β moments in the case A.

N_2), respectively. Its minimization was performed with the help of the MINUIT routine.[19]

The errors on the matrix elements were estimated by considering 1 standard deviation (χ^2 function increased by unity from its absolute minimum) in addition to the uncertainty in the axial-vector coupling constant ($g_A/g_V = -1.19 \pm 0.03$). The normalization parameter η was determined from the observed half-life t and the integrated spectrum $C_\beta(W)$,

$$\eta^2 = \frac{6222}{tf_c} \tag{18}$$

with

$$f_c = \int_1^{W_0} C_\beta(W)\, pWq^2 F(Z,W)\, dW\,. \tag{19}$$

The analysis has gone through the following steps:

Case A. The expression (17) has been minimized by taking the matrix element ratios Λ, u, and z as free parameters.

Case B. The ratio Λ has been fixed at the value $\Lambda = 2.22$, which corresponds to an energy $E_\gamma = 14.95$ MeV of the IA state to the ground state as measured by Ejiri *et al.*[11] The remaining parameters (z and u) were taken as free.

Case C. Besides taking a fixed value for the ratio $\Lambda = 2.22$ we also supposed that the ratio u was equal to its single-particle value $[(u)_{\text{s.p.}} = -g_A/g_V]$. The only free parameter was the ratio z.

Case D. The matrix-element parameters u and z were fixed at the values $(u)_{\text{s.p.}} = -g_A/g_V$, $(z) = -(18/5)^{1/2} g_A/g_V$, while the ratio Λ was freely varied.

The results are displayed in Table I. It can be seen that in every case, except in the last one (case D) the experimental data are satisfactorily reproduced. In order to have a better fitting for the nuclear orientation measurement in the case D, we have also minimized the function

$$\chi^2_T = \frac{\chi^2(C_\beta)}{N(C_\beta)} + \frac{\chi^2(N_e)}{N(N_e)}\,, \tag{20}$$

where $N(C_\beta) = 40$ and $N(N_e) = 2$ are the numbers of the experimental points considered for the observables C_β and N_e, respectively. The results of this minimization are quoted as case D′ in Table I.

In the present analysis we have neglected the third-forbidden β moments and the matrix elements of the form $\langle 0(\lambda)(r/r_0)^n\rangle$ have been approximated as

$$\left\langle 0(\lambda)\left(\frac{r}{r_0}\right)^n\right\rangle = \langle 0(\lambda)\rangle\,. \tag{21}$$

This means that we have fixed the ratio ϵ_1 at the value $\epsilon_1 = 1$. Both approaches are justified in spite of the pronounced cancellation effect observed in this transition, due to the fact that $r_0 p_{\max} \approx 0.03 \ll |Y|$. In addition, there is no known mechanism which would be expected to reduce the first-forbidden β moments without also reducing the third-forbidden β moments, and the introduction of additional nuclear parameters decreases the selectivity of a χ^2 test.

IV. DISCUSSION

The reduction of the experimental β moments as compared with the calculated values is often discussed in terms of the effective coupling constants $(g^{\text{eff}}_{V,A})_\lambda$ defined as

$$\frac{\langle 0(\lambda)\rangle_{\text{exp}}}{\langle 0(\lambda)\rangle_{\text{cal}}} = (g^{\text{eff}}_{V,A})_\lambda / g_{V,A} = 1 + (\chi_{V,A})_\lambda\,, \tag{22}$$

where $(\chi_{V,A})$ is the polarizability induced by a field

TABLE I. β moments for the $\frac{7}{2}^- - \frac{5}{2}^+$ β transition in ^{141}Ce and ^{139}Ba, in Fermi units.

	^{141}Ce					^{139}Ba [a]	
	Case A	Case B	Case C	Case D	Case D′ [b]	Case A′	Case B′ [b]
$\langle i\vec{r}\rangle_{\text{exp}}$	0.98 ± 0.20	1.02 ± 0.11	1.08 ± 0.02	1.10 ± 0.01	0.75	0.78 ± 0.16	1.16
$\langle \vec{\sigma}\times\vec{r}\rangle_{\text{exp}}$	-1.11 ± 0.35	-1.11 ± 0.15	-1.08 ± 0.06	-1.10 ± 0.05	-0.75	-1.74 ± 0.26	-1.52
$\langle iB_{ij}\rangle_{\text{exp}}$	1.30 ± 0.50	1.20 ± 0.30	1.20 ± 0.20	2.10 ± 0.10	1.44	1.94 ± 1.30	1.40
$\xi^{-1}\langle\vec{\alpha}\rangle_{\text{exp}}$	2.16 ± 0.45	2.19 ± 0.23	2.23 ± 0.08	2.27 ± 0.05	1.65	2.81 ± 0.16	3.12
Λ_{exp}	2.28 ± 0.53	2.22	2.15 ± 0.05	2.12 ± 0.02	2.28	3.74 ± 0.70	2.65
$(\chi_V)_{\lambda=1}$	-0.63 ± 0.08	-0.61 ± 0.05	-0.59 ± 0.02	-0.60 ± 0.01	-0.71	...	...
$(\chi_A)_{\lambda=1}$	-0.59 ± 0.11	-0.58 ± 0.05	-0.59 ± 0.02	-0.60 ± 0.01	-0.71	...	...
$(\chi_A)_{\lambda=2}$	-0.69 ± 0.12	-0.71 ± 0.07	-0.71 ± 0.04	-0.60 ± 0.01	-0.71	...	...
$\log[f_c t/(ft)_{\text{exp}}]$	1.24	1.25	1.20	1.19	2.51	0.82	0.64
Y	-0.78	-0.77	-0.81	-0.92	0.98	...	...
$\chi^2(C_\beta)$	30.2	30.2	30.2	32.9	65.8	...	...
$\chi^2(N_e)$	0.10	0.10	0.10	8.4	1.74	...	...

[a] Results obtained by Sunier and Berthier (Ref. 14).
[b] No errors on the β moments are given.

with the structure characteristic of the β moment in question. As the effect of the quadrupole-quadrupole interaction is negligible in the present case,[4-6] the term $\langle 0(\lambda)\rangle_{cal}$ implies the single-particle value of the moment $0(\lambda)$ corrected by the pair correlations, i.e.,

$$\langle 0(\lambda)\rangle_{cal} = \langle (2d_{5/2})_p \| 0(\lambda) \| (2f_{7/2})_n\rangle U_p(2d_{5/2}) U_n(2f_{7/2}) . \quad (23)$$

Using Rho's value[4] for the vacancy: $U_p(2d_{5/2}) = 0.82$ and $U_n(2f_{7/2}) = 1.0$ and employing radial wave functions in the Woods-Saxon potential with standard parameters ($\langle 2d_{5/2}|r|2f_{7/2}\rangle = 4.82$ fm) we obtain

$$\begin{aligned} \langle i\vec{r}\rangle_{cal} &= 2.60 \text{ fm}, \\ \langle \vec{\sigma}\times\vec{r}\rangle_{cal} &= -2.60 \text{ fm}, \\ \langle iB_{ij}\rangle_{cal} &= 4.20 \text{ fm}, \\ \epsilon_1(\text{WS}) &= 1.15 . \end{aligned} \quad (24)$$

The polarizabilities calculated in this way are shown in Table I. The assumptions made in the previous section correspond to

$$(\chi_A)_{\lambda=1} = (\chi_V)_{\lambda=1} , \quad (25)$$

and

$$(\chi_A)_{\lambda=2} = (\chi_A)_{\lambda=1} = (\chi_V)_{\lambda=1} , \quad (26)$$

for the cases C and D(D′), respectively. Considering as statistically significant only those solutions that fulfill the condition

$$\frac{\chi^2(C_\beta)}{N(C_\beta)} \leq 1, \quad \frac{\chi^2(N_e)}{N(N_e)} \leq 1, \quad (27)$$

it follows from Table I that the equality (26) is not consistent with the experimental data.

In Table I we also present the results for the β moments for the $\frac{7}{2}^-(2.23 \text{ MeV})\frac{5}{2}^+$ transition from the decay of ^{139}Ba. They have been obtained by Sunier and Berthier[14] after analyzing the shape factor $C_\beta(W)$ and the angular correlation parameter $\epsilon(W)$. The cases A′ and B′ are equivalent to our A and B, respectively. In the last case the Λ ratio was fixed at the value $\Lambda = 2.65$ which corresponds to the Fujita-Eichler estimate.[20]

Comparing our results with the ones obtained by Sunier and Berthier, and considering how difficult the extraction of the β moments from the experimental data is, it is encouraging to observe such a close correspondence between the β matrix elements for ^{139}Ba and ^{141}Ce.

The β moment $\langle i\vec{r}\rangle_\beta$ obtained by Ejiri *et al.*,[11] from the measurement of the $E1$ γ moment $\langle i\vec{r}\rangle_\gamma$ from the IA state, and on the basis of equation (10), $\langle i\vec{r}\rangle_\beta = 0.64 \pm 0.16$ fm, is in fair agreement with our result: $\langle i\vec{r}\rangle_\beta = 0.98 \pm 0.20$ fm. This fact

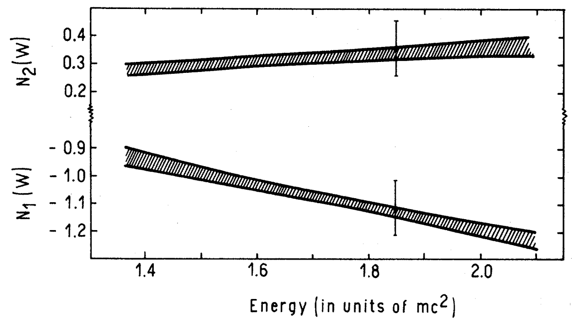

FIG. 4. Calculated values of the longitudinal polarization with the β moments in the case A.

confirms the assumption $|\text{IA}\rangle = (2T_i)^{-1/2}\, T_-|i\rangle$ or, equivalently, the validity of the expression (10) (CVC theory).

The core-polarization effects induced by the isospin and spin-dependent interactions $H_\tau = \kappa_\tau \vec{\tau}_1\cdot\vec{\tau}_2\vec{r}_1\cdot\vec{r}_2$ and $H_{\tau\sigma} = \kappa_{\tau\sigma}\vec{\tau}_1\cdot\vec{\tau}_2\vec{\sigma}_1\cdot\vec{\sigma}_2\vec{r}_1\cdot\vec{r}_2$ have been recently evaluated by Ejiri[13] in the random phase approximation. Using the first Hamiltonian, with $\kappa_\tau = 0.17$ fm^{-2} MeV, he calculated the charge-dependent polarizability for the $\frac{7}{2}^- \to \frac{5}{2}^+$ transition in ^{141}Ce and obtained the value $(\chi_V)_{\lambda=1} = -0.68$, which agrees with our result.[21]

Evaluating the polarizability $(\chi_A)_{\lambda=1}$ in the same way[6] and from the relation $(\chi_A)_{\lambda=1} \approx (\chi_V)_{\lambda=1}$ (see Table I), it follows that

$$\frac{\kappa_{\tau\sigma}}{\kappa_\tau} \approx 0.9 , \quad (28)$$

which is in accordance with the value $\kappa_{\tau\sigma}/\kappa_\tau = 0.85$ deduced by Ejiri from the analysis of the unique first-forbidden β decays in the mass region $A \approx 90$.[13]

The reduction in the β-transition matrix element in the lead region, has been recently discussed by Damgaard, Broglia, and Riedel.[22] They obtained two solutions

$$\begin{aligned} (\chi_V)_{\lambda=1} &= -0.5 , \quad (\chi_A)_{\lambda=1} = -0.6 , \\ (\chi_V)_{\lambda=1} &= -0.8 , \quad (\chi_A)_{\lambda=1} = -0.4 . \end{aligned} \quad (29)$$

The first of them is consistent with the present study.

Regarding the ratio Λ, it has not been possible to distinguish between the Fujita-Eichler approach ($\Lambda = 2.40$) and an estimate based on the Damgaard-Winther approximation [$\Lambda = 1.95$ with $\epsilon_1(\text{WS}) = 1.15$]. Further measurements on the distribution of electrons from the oriented nuclei and their longitudinal polarization, both as a function of energy, could provide the necessary additional information. The predicted values of these observables are presented in Figs. 3 and 4.

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[19]Kindly provided to us by Dr. F. James and Dr. M. Roos, from CERN.

[20]The pair corrections for ^{139}Ba are $U_p(2d_{5/2}) = 0.88$ and $U_n(2f_{7/2}) = 1$ (Ref. 4).

[21]We prefer to speak in terms of the polarizabilities instead of the effective coupling constants due to the difference between the "bare" vector and axial-vector coupling constants. The sign of the polarizability is opposite to that of the strength of the residual interaction, and a repulsive coupling ($\eta > 0$) implies, for low frequencies, destructive interference between the polarization effect and one-particle moment. For more details on this subject see A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1968), Vol. I; *ibid.*, Vol. II, to be published.

[22]J. Damgaard, R. Broglia, and C. Riedel, Nucl. Phys. A135, 310 (1969).