COLLECTIVE EFFECTS IN THE Cs^{131} NUCLEUS

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Some new data for the Cs^{131} nucleus are inconsistent with the theoretical assignment of all Cs^{131} levels to a single rotational band of an asymmetric nucleus.[9] A new transition is observed at 907 keV; the half-life of the 1039-keV level is $T_{1/2} < 2 \times 10^{-9}$ sec; the γ transition intensity ratio $I_{\gamma 918}/I_{\gamma 907} = 14.5 \pm 3$ is determined. $T_{1/2} = (13.5 \pm 0.5) \times 10^{-9}$ sec is confirmed for the 133-keV level. However, the probabilities B(E2) of the 124- and 133-keV transitions, and also the ratio $B(E2)_{exp}/B(E2)_{shell\text{-}mod} > 1$ for the 495-keV transition, indicate collective effects in the Cs^{131} nucleus. A more adequate model should take into account the interactions of rotational, vibrational, and single-particle motions.

Measurements of the Cs^{133} 438-keV level half-life and the ratio $B(E2)_{exp}/B(E2)_{shell\text{-}mod}$ for the 356-keV transition are presented.

INTRODUCTION

IT has been shown by the study of even-even nuclei in the regions $A \leq 150$ and $A \geq 190$ that the properties of their excited levels can be accounted for by considering the rotational motion of nonaxial (nonaxially symmetric) nuclei [1] or nuclear vibrations.[2,3] Table I gives the probability ratios $B(E2)_{exp}/B(E2)_{shell\text{-}mod}$ of experimental and calculated shell-model transitions from the first excited levels of even-even nuclei in the region of A close to Cs^{131}.[4-6]

The analogous treatment of odd-A nuclei is complicated by the fact that the energy states of the odd nucleon must be taken into account in addition to collective nuclear motion. One method considers the coupling between internal motion and quadrupole vibrations.[3,7] The properties of odd-A nuclear states are greatly dependent on the coupling parameter. Attempts have recently been made to use the Davydov model [1] to describe the energy levels of odd-A nuclei as rotational states of nonaxial nuclei.[8,9]

Person and Rasmussen[9] have studied in detail the levels and electromagnetic transitions of Cs^{131}, and have attempted to assign all Cs^{131} levels to a single ground-state rotational band of a nonaxial nucleus. They assumed the strong-coupling approximation in which the internal nuclear structure is unaffected by the rotational motion. Hecht and Satchler[8] have made a similar investigation of odd-A nuclei close to A = 190. Both investigations employed the odd-nucleon energy states calculated by Newton[10] assuming for the independent-particle model that the Hamiltonian consists of an anisotropic oscillator potential plus the spin-orbit terms Cls and Dl^2. Person and Rasmussen disregarded vibration-rotation coupling. It is of interest to compare the theoretical results with experiment.

EXPERIMENT AND DISCUSSION OF RESULTS

Figure 1 shows the Cs^{131} level scheme including our present results. Person and Rasmussen used the positions and spins of the 124- and 133-keV levels and the ground-state spin to obtain the parameters β and γ for their model as a basis for calculating the spins and energies of succeeding states. The two principal doubtful assumptions of their model are the characteristics of the 1039-

Table I

Nucleus	$2^+ \to 0^+$ transition energy, keV	$B(E2)_{exp}/B(E2)_{shell\text{-}mod}$	Nucleus	$2^+ \to 0^+$ transition energy, keV	$B(E2)_{exp}/B(E2)_{shell\text{-}mod}$
$_{52}Te^{120}$	560	31	$_{54}Xe^{130}$	535	24
Te^{122}	570	26	Xe^{132}	673	17
Te^{124}	608	21	$_{56}Ba^{130}$	359	36
Te^{126}	662	25	Ba^{132}	470	36
Te^{128}	750	18	Ba^{134}	600	33
Te^{130}	850	15	Ba^{136}	820	24
			Ba^{138}	1420	12

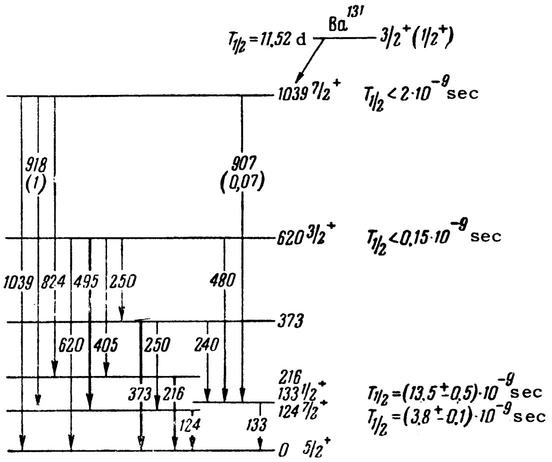

FIG. 1. Cs^{131} level scheme.

and 133-keV levels and the types of transitions from these levels. If the Person-Rasmussen model is correct the $7/2^+$ 1039-keV level should decay mainly to a (supposedly) $7/2^+$ 133-keV level.[9] Although 918-124-keV γ-ray coincidences had previously been observed,[11] Person and Rasmussen suggested the existence of a 907-133-keV cascade.

After the half-life $T_{1/2} = (13.3 \pm 0.5) \times 10^{-9}$ sec of the 133-keV level was measured,[12] it became possible to determine accurately the decay curve of the 1039-keV level, keeping in mind also that the half-life of the 124-keV level is $(4 \pm 0.3) \times 10^{-9}$ sec.[11] The delayed coincidences of the 918-124-keV and 907-133-keV cascades were plotted. Two NaI(Tl) crystals and an FÉU-33 photomultiplier were used to detect γ quanta of about 910 and 130 keV. One channel registered 918-907-keV coincidences, while the other channel registered 124-133-keV coincidences. Both channels were connected to a fast-slow coincidence circuit with the resolving time $2\tau = 1 \times 10^{-8}$ sec. The measurements are represented in Fig. 2, which indicates two half-lives:

$$T_{1/2\,124} = (3.8 \pm 0.1)\cdot 10^{-9}\,\text{sec}, \quad T_{1/2\,133} = (13 \pm 1)\cdot 10^{-9}\,\text{sec};$$

this indicates a 907-keV transition between the 1039- and 133-keV levels. Figure 2 shows the γ-intensity ratio of the 907- and 918-keV transitions.

The calculation of the delayed coincidence curves requires the knowledge of two parameters: the photomultiplier time fluctuation Δt_f and the number K of photoelectrons resulting from a 1-keV γ-ray energy loss in the crystal.[11,13] Assuming $\Delta t_f = 4 \times 10^{-9}$ sec and $K = 2$, we obtain good agreement between the calculated curve and experiment for simultaneous coincidences (Co^{60}) with the resolving time $2\tau = 10^{-8}$ sec (curve 1 of Fig. 2), and for delayed 918-124-keV coincidences with $T_{1/2\,124} = 3.8 \times 10^{-9}$ sec. Curve 3 of Fig. 2 was calculated for 907-133-keV coincidences with $T_{1/2\,133} = 13.5 \times 10^{-9}$ sec.

The calculated sum curve 4 is found to fit the experimental points if we assume

$$N_{\text{coinc }918-124}/N_{\text{coinc }907-133} = 18.5 \pm 4.$$

This ratio yields

$$\frac{I_{\gamma 918}}{I_{\gamma 907}} = \frac{N_{\text{coinc }918-124}}{N_{\text{coinc }907-133}} \frac{1+\alpha_{124}}{1+\alpha_{133}}.$$

Assuming that the 124-keV transition is of the type M1 with the total conversion coefficient $\alpha_{124} = 0.5$ and that the 133-keV transition is E2 with $\alpha_{133} = 0.9$, we obtain the intensity ratio

$$I_{\gamma 918}/I_{\gamma 907} = 14.5 \pm 3.$$

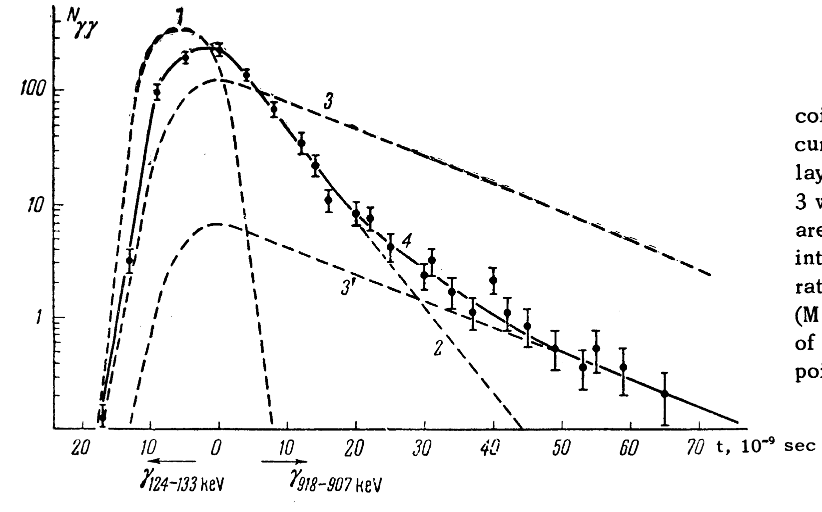

FIG. 2. Delayed 918-907-keV and 124-133-keV γ-γ coincidences for Cs^{131}. Curves 1—3 were calculated; curve 1 for simultaneous coincidences, curve 2 for delayed coincidences with $T_{1/2} = 3.8 \times 10^{-9}$ sec, and curve 3 with $T_{1/2} = 13.5 \times 10^{-9}$ sec. The areas under the curves are equal. Curve 3' was derived from curve 3 by taking into account the 918-kev/907-keV γ-transition intensity ratio and the conversion coefficients of the 124-keV (M1) and 133-keV (E2) transitions. Curve 4 is the sum of curves 2 and 3' passing through the experimental points.

Table II

Nucleus	I_i	I_f	Transition energy, keV	$B(E2)_{exp}/B(E2)_{shell-mod}$	$B(M1)_{exp}/B(M1)_{shell-mod}$
$_{55}Cs^{131}$	$7/2^+$	$5/2^+$	124	19	1/530
	$1/2^+$	$5/2^+$	133	6	
Cs^{133}	$5/2^+$	$7/2^+$	81	25	1/600
	$1/2^+$	$5/2^+$	356	>4.5	
Cs^{135}	$5/2^+$	$7/2^+$	250	38	1/340

This ratio disagrees with the result derived from the Person-Rasmussen model.

Since the spin of Ba^{131} is 3/2 or 1/2 and electron capture into the 1039-keV level is weak, the spin of this level is large ($7/2^+$).[9] If the 124-keV level has spin 7/2, a 918-keV transition with a short half-life is possible. We verified this by measuring the half-life of the 1039-keV level using delayed coincidences. By studying the slope of the $X_{capt\,(30\ keV)} - \gamma_{1039\ keV}$ coincidence curve we obtained

$$T_{1/2\,1039} < 2\cdot 10^{-9}\ \text{sec}.$$

Our results thus indicate that a large spin does not belong to the 133-keV level but to the 124-keV level, and that its probable value is $7/2^+$ (see also below).

Collective effects in a slightly deformed odd-A nucleus can result in accelerated E2 transitions like those encountered in neighboring even-even nuclei. (See Tables I and II for Z close to 55.) Table II shows that decays of the first excited levels of Cs^{133} and Cs^{135} [14] are M1 + E2 transitions, where the M1 transitions are hindered and the E2 admixture is accelerated 25—38 times.

In order to determine whether the 356-keV E2 transition of Cs^{133} is accelerated, we measured the half-life of the 438-keV level, obtaining

$$T_{1/2\,438} < 1.5\cdot 10^{-10}\ \text{sec},$$

which gives

$$B(E2)_{\exp\ 356}/B(E2)_{\text{shell-mod}\ 356} > 4.5.$$

The technique was the same as that used in measuring the lifetime of the Cs^{131} 620-keV level (see below).

Accelerated E2 transitions should be observed in Cs^{131}. This follows from the calculations of Person and Rasmussen, who give the probabilities B(E2) for the $1/2^+ \to 5/2^+$ and $7/2^+ \to 5/2^+$ transitions as functions of the parameters γ for the deformation $\beta = 0.3$. For the $7/2^+ \to 5/2^+$ 133-keV transition they find that the E2 transition is accelerated 400 times compared with the shell model; this is large compared with corresponding results for neighboring nuclei. The experimental result does not approach this value even if we assume a pure E2 133-keV transition. However, if a 5% M1 admixture is assumed, we find that $7/2^+ \xrightarrow{133\ \text{keV}} 5/2^+$ is hindered by a factor of 4×10^3 compared with the shell model; this is also too large (see Table II).[11,15] Therefore, as suggested in [9], the lifetime of the 133-keV level had to be determined more precisely.

The half-life of this level was measured by means of the 907-133-keV coincidences (Fig. 2). A similar measurement, but with better statistics, was performed using 480-133-keV γ-γ coincidences; this yielded

$$T_{1/2\,133} = (13.5 \pm 0.5)\cdot 10^{-9}\ \text{sec}.$$

The result given in [12] was thus confirmed within experimental error.

It can therefore be affirmed that the pure rotational model of Person and Rasmussen does not account for the characteristics of the 133-keV level if the assignment $7/2^+$ is made. We have already mentioned that the 907-keV γ transition is weaker than the 918-keV transition; this also conflicts with the $7/2^+$ assignment to the 133-keV level.

A different assignment can be based on the measurements of the angular 495-124-keV γ-γ correlation in [16]. These results indicate that the 124-keV level has spin 7/2 and that the 124-keV transition is of the type M1 (97%) + E2 (3%), thus indicating an acceleration of the order 20 for the E2 transition, in agreement with Tables I and II. The M1 component is forbidden; this situation can be accounted for by assuming that the 124-keV level has independent-particle character.[11,15]

Correlation measurements show that the 495-keV transition is of the E2 type.[16]

For the purpose of determining the probability $B(E2)_{exp}$ of $X_{capt\ 30\ keV} - \gamma_{495\ keV} - \gamma_{124\ keV}$ triple coincidences we measured the half-life of the 620-keV level. This procedure was used to exclude coincidences between 495-keV γ rays and x rays from internal conversion of the 124-keV transition with $T_{1/2} = (3.8 \pm 0.1)\times 10^{-9}$ sec; we have described a very similar procedure in [17].

Figure 3 shows the experimental results for the triple coincidences and simultaneous 30-495-keV γ-γ coincidences in the case of Na^{22} (the continuous curve). A shift of the center of gravity yields

$$T_{1/2\,620} < 1{,}5 \cdot 10^{-10} \text{ sec},$$

whence

$$B(E2)_{\text{exp } 495} / B(E2)_{\text{shell-mod } 495} > 1.$$

Then, by assigning $7/2^+$ to the 124-keV level, we can account for the 918-keV/907-keV transition intensity ratio, the γ-γ correlation measurement,[16] and the acceleration of 124-keV and 495-keV E2 transitions (Table II). It should be noted that if we assign $1/2^+$ to the 133-keV level with $T_{1/2\ 133} = (13.5 \pm 0.5) \times 10^{-9}$ sec we find that the E2 transition is accelerated 6 times compared with the independent-particle model. A comparison with the Person-Rasmussen model yields

$$B(E2)_{\text{exp}} / B(E2)_{\text{PR}} = {}^{1}/_{3}.$$

For a better understanding of the Cs^{131} decay scheme it is important to know the properties of M1 transitions, which are not discussed in[9]. It is difficult to account for the forbiddenness of the 620-keV M1 transition on the basis of the independent-particle model if $3/2^+$ is assigned to the 620-keV level.[9,16]

In the collective (vibrational or nonaxial) models of even-even nuclei we find that M1 transitions are highly forbidden, although they are allowed by parity and angular momentum. Similar forbiddenness can also be assumed for odd-A nuclei. The forbiddenness of the 279-keV M1 ($3/2 \rightarrow 1/2$) transition in the odd-mass nucleus Tl^{203} is accounted for by de Shalit[18] on the basis of the fact that M1 transitions cannot occur between states connected by phonon transitions. In the specific case of Cs^{131} it would be desirable to have quantitative results regarding M1 transitions.

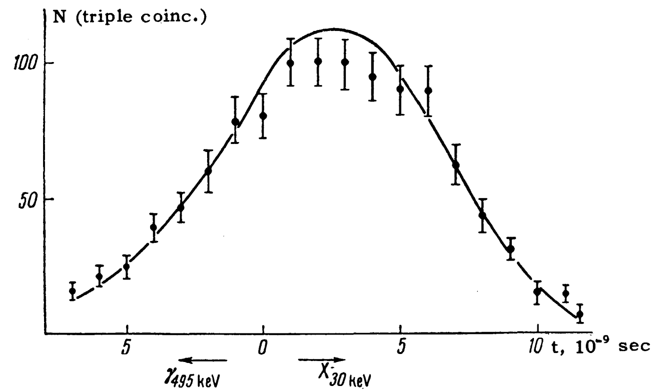

FIG. 3. $X_{capt\ (30\ keV)} - \gamma_{495\ keV} - \gamma_{124\ keV}$ triple coincidences for Ba^{131} (experimental points), and $\gamma_{30\ keV} - \gamma_{495\ keV}$ simultaneous coincidences for Na^{22} (curve).

For the magnetic moment of the Cs^{131} ground state (μ_{exp} = 3.48 nuclear magnetons[9]) a calculation based on the Person-Rasmussen model gives $\mu = 2.82$ if it is assumed that the proton has $g_s = 4$, which Person and Rasmussen consider the most suitable g_s-factor to account for the magnetic moment of the odd-Z nucleus. The value of μ cannot be calculated using the model of Choudhury,[7] who considered a nucleon having angular momentum j coupled with the nuclear vibrational motion. He calculated the wave functions of the system, the energy states, and the magnetic moments as functions of the coupling parameter X for the case j = 5/2 (which corresponds to Cs^{131}), and obtained a series of energy levels with spins 5/2 (the ground level), 7/2, 1/2, 9/2, 3/2, and 5/2. Assuming intermediate coupling with the parameter X = 1, we obtain for the ground state $\mu = 3.52$ (with $g_s = 4$), which is close to the experimental result.

CONCLUSION

The observed E2 transitions of Cs^{131} (124, 133, and 495 keV) are accelerated compared with the independent-particle model, thus indicating the existence of collective effects in the Cs^{131} nucleus. In the present work it has been shown that the intensity ratio of 918- and 907-keV γ transitions from the 1039-keV level and the characteristics of the 133-keV level are not accounted for by the pure rotational model of Person and Rasmussen. It has been fairly well established that the 133-keV rotational level in the latter model cannot have the assignment $7/2^+$.

Our measurements together with those in[16] yield the assignment $7/2^+$ for the 124-keV level ($T_{1/2} = (3.8 \pm 0.1) \times 10^{-9}$ sec). From the forbiddenness of the 124-keV M1 transition, representing an l-forbidden M1 transition ($g_{7/2} \rightarrow d_{5/2}$)[11,15] we conclude that the internal structure of the nucleus is changed when it decays from the 124-keV level to the ground state. It would be interesting to repeat the calculations of Person and Rasmussen taking into account the existence of two close-lying independent-particle levels (the ground state and the excited 124-keV level).

One should also take into account the vibration-rotation interactions that are observed in asymmetric even-even nuclei.[19] An attempt can also be made to account for the characteristics of Cs^{131} levels using a pure vibrational model that takes into account interactions between vibrations and single particles; the properties of this model depend on the degree of coupling.[3,7]

For any model one must know the probabilities of Cs^{131} M1 transitions, particularly for the 620-keV transition. Angular γ-γ correlations are being measured in a further study of the 124- and 620-keV levels.

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