Medium-spin structure of ^{145}Cs

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Excited states in ^{145}Cs, populated following the spontaneous fission of ^{248}Cm, were studied by means of prompt-γ spectroscopy, using the EUROGAM2 multidetector array. A new level scheme of ^{145}Cs was proposed. We identified a decoupled band corresponding to 1/2 [550] proton configuration and interpreted the ground-state band as a mixed configuration of 1/2 [440] and 3/2 [422] proton orbitals. Quasiparticle-rotor calculations performed for ^{145}Cs support such assignments. The electric dipole moment in ^{145}Cs, $D_0 = 0.013(4)$ efm, is smaller than in lighter Cs isotopes, which suggests that octupole correlations in Cs isotopes decrease at the neutron number $N = 90$, similarly as observed in the ^{146}Ba and ^{147}La isotones.

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Odd-A Cs nuclei were studied previously in our measurement of γ rays from fission of ^{248}Cm [1] and by Hwang *et al.* [2] in fission of ^{252}Cf. These works did not report on the level of octupole correlations in Cs. Such correlations are strong in the neighboring Ba nuclei [3,4] and, according to calculations [5], the neutron-rich Cs isotopes should have octupole deformation in their ground states. To determine the strength of octupole correlations in odd-A Cs isotopes, we performed a higher-statistics, ^{248}Cm fission measurement [6] and found [7,8] parity-doublet-like structures in ^{141}Cs and ^{143}Cs. However, the $E1$ transition rates in these nuclei appeared to be about an order of magnitude smaller than in Ba isotones. In contrast, $B(E1)$ rates in ^{142}Xe [9] are as high as in ^{144}Ba [3,4], suggesting that octupole correlations in odd-Z nuclei in this region are lower than in even-Z nuclei. A possible explanation is "blocking" of the octupole-driving, $\Delta j = 3$ pair of proton orbitals ($d_{5/2}$, $h_{11/2}$), which are responsible for octupole correlations in this region. A similar effect was found in our recent study of ^{95}Y [10], where the ($p_{3/2}$, $g_{9/2}$), $\Delta j = 3$ proton pair is active.

Of two different theoretical predictions for Cs nuclei, one forecasts that octupole correlations increase at higher neutron number [11,12], while the other anticipates that at neutron number $N = 90$ the $B(E1)$ rates may decrease because of a specific cancellation of an electric dipole moment at $N = 90$ [13,14]. The latter effect was observed in the neighboring ^{146}Ba, where $B(E1)$ rates are an order of magnitude smaller than in ^{144}Ba [3,4]. In addition to octupole effects, there is also an onset of quadrupole deformation around $N = 90$ in this region. Therefore, it is not obvious how the structure of Cs isotopes with $N > 88$ will look. In this work we report on the study of ^{145}Cs and partially answer this question.

We studied excited states in ^{145}Cs using the data from a measurement of high-fold, γ coincidences following spontaneous fission of ^{248}Cm, performed using the EUROGAM2 array [15]. For more information on the experiment and the data analysis see Ref. [6].

The data obtained in this work allowed the modification of the excitation scheme of ^{145}Cs. The new level scheme is shown in Fig. 1. In this scheme, we introduced a new ground-state transition of 55.5 keV, based on the observation of a new, 55.5-keV line, which is coincident with most of other lines in ^{145}Cs. Consequently, all excited levels reported in Ref. [1] were shifted upward by 55.5 keV. In Fig. 2, we show a γ-ray spectrum measured by a low-energy photon spectrometer (LEPS), which was doubly gated on the 192- and 325-keV lines of ^{145}Cs. The location of the 55.5-keV transition is supported further by the observation of a 144.2-keV decay from the 144.2-keV level.

A new decay branch of the 607.0-keV level (550.8-keV level in Ref. [1]) was found. In Fig. 2 there is a new line at 91.2 keV. Figure 3 shows a spectrum gated on the 88.7- and 91.2-keV lines, where a new line at 371.4 keV and other lines of ^{145}Cs are seen. We place the 91.2-keV transition above the 371.4-keV transition. Such an order is consistent with the observed branching ratios, but we cannot prove that the reverse order is not possible.

Fitting two Gaussian shapes to the 192-keV doublet in Fig. 2 provided energies of 191.0(2) keV and 192.0(2) keV. In Fig. 3 one observes a line at 191.0 keV. This indicates that the 191.0-keV line is above the 192.0-keV line in the excitation scheme. We also observe a new 389.5-keV transition in the ground-state band, two more transitions of 534.5 and 598.7 keV in the yrast cascade, and a new cascade of 290.8-, 297.8-, 447.8-, and 574.8-keV transitions. The new lines are shown in Fig. 4. Table I shows branching ratios for decays from the excited states of ^{145}Cs, as observed in this work.

The $3/2^+$ spin and parity of the ground state of ^{145}Cs were obtained with the atomic-beam magnetic-resonance technique, which indicated a dominant 3/2 [404] Nilsson configuration for this level [16,17]. In the LEPS spectrum gated on the

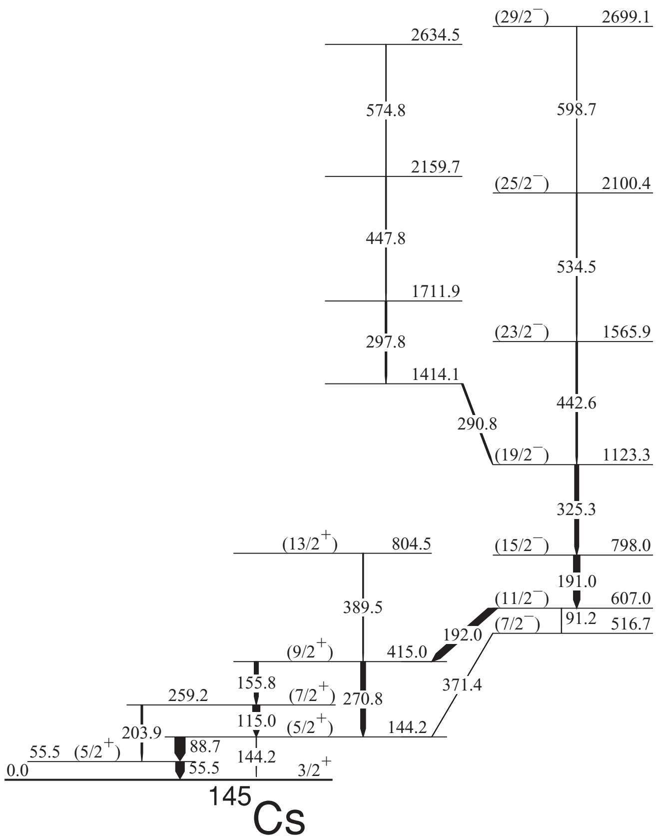

FIG. 1. Partial level scheme of ^{145}Cs as obtained in the present work.

88.7- and 115.0-keV lines, shown in Fig. 5, there is the 55.5-keV line and the corresponding K_α and K_β x-ray lines of Cs. From the observed intensities of these lines, we obtained a conversion coefficient of $\alpha_K = 3.8(14)$ for the 55.5-keV line. In the error bar we included the uncertainty owing to the contribution from the conversion of the 155.8-keV line. The experimental value, compared to the theoretical α_K values of 0.94, 4.21, and 5.98 for $E1$, $M1$, and $E2$ multipolarities, respectively, favors an $M1 + E2$ multipolarity

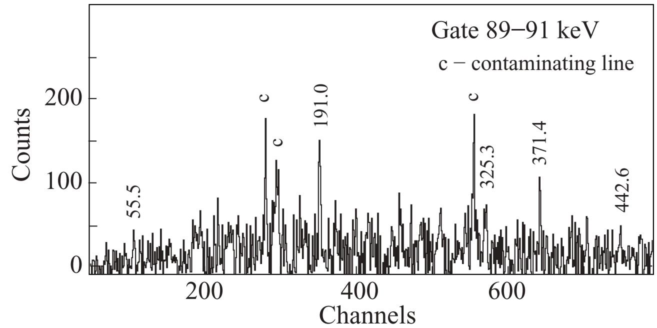

FIG. 3. A γ-ray spectrum double gated on 88.7- and 91.0-keV lines in ^{145}Cs. Lines are labeled in keV. See the text for further explanations.

for the 55.5-keV transition. A similar analysis provides an $\alpha_K = 2.3(9)$ conversion coefficient for the 88.7-keV transition. The theoretical values are 0.26, 1.09, and 1.73 for $E1$, $M1$, and $E2$ multipolarities, respectively. Therefore, the experiment indicates an $M1 + E2$ multipolarity for the 88.7-keV transition.

We used a technique of $\gamma\gamma$ angular correlations described in more detail in Refs. [6,18] to show that the 191.0-keV transition has a quadrupole (Q) multipolarity, while the 192.0-keV transition is a dipole (D). Four two-dimensional $\gamma\gamma$ histograms, with angles of 90°, 60° (or 120°), 30° (or 150°) and 0° (or 180°) between the two γ rays in the cascade, respectively, were sorted. The peak intensities in these histograms, properly normalized, provided angular correlations for $\gamma\gamma$ cascades. Figure 6(a) shows angular correlations between the 191.0- and 192.0-keV lines. The data points, which represent intensities of the (191–192)-keV peak in angular-correlation histograms, are compared to the theoretical [18,19] correlations for the quadrupole-stretched dipole (QD1) cascade, the quadrupole-unstretched dipole (QD2) cascade, the quadrupole-quadrupole (QQ) cascade, and the stretched-dipole-stretched-dipole (DD) cascade. The experiment agrees well with the prediction for the QD1 cascade. To find which of the two lines, 191.0 or 192.0 keV, is a quadrupole and which is a dipole, we gated in the correlation histograms on the 325.3-keV line and fitted intensities of the lines in the

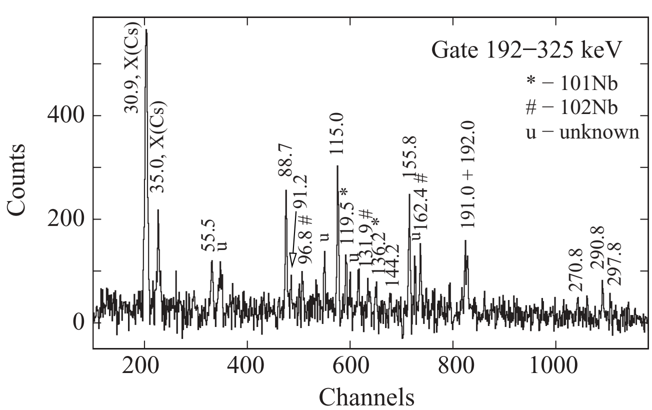

FIG. 2. LEPS spectrum double gated on the 192- and 325-keV γ lines of ^{145}Cs. Energies are labeled in keV. See text for further explanations.

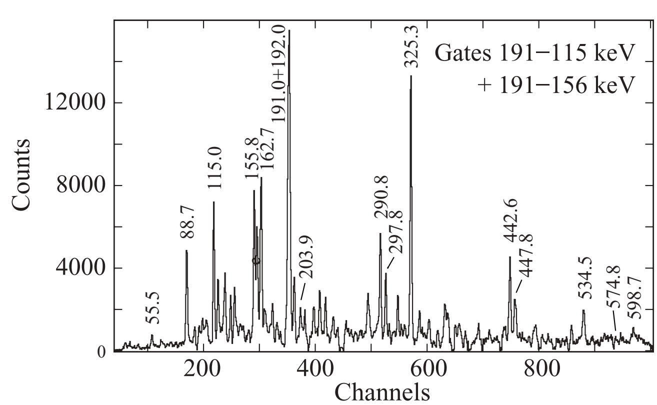

FIG. 4. Double-gated γ-ray spectrum with the first gate on the 191-keV line and the second on the 115- and 156-keV lines. Lines in the spectrum are labeled in keV. See the text for further explanations.

TABLE I. Branching ratios for levels in the ^{145}Cs nucleus, as observed in this work.[a]

E_{exc} (keV)	E_γ (keV)	I_γ (arb. units)	E_{exc} (keV)	E_γ (keV)	I_γ (arb. units)
144.3	144.2	100(12)	415	270.8	100(5)
	88.7	1780(70)		155.8	336(8)
259.2	203.9	100(6)	607.0	91.2	100(12)
	115.0	502(10)		192.0	730(50)

[a] I_γ values are given in arbitrary units; exc, excited state.

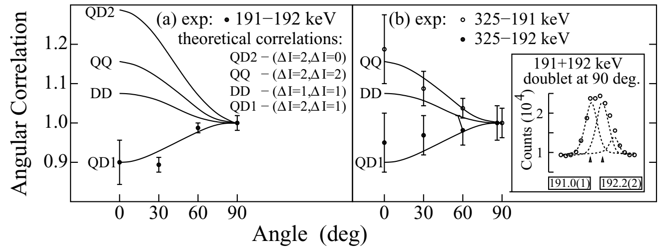

FIG. 6. Angular correlations between the 191.0-, 192.0-, and 325.3-keV lines of ^{145}Cs, as observed in this work. Theoretical correlations are for unmixed transitions. See text for further explanations.

(191 + 192)-keV doublet. The resulting correlations for the (325.3–191.0)-keV cascade, shown in Fig. 6(b), agree with the QQ calculation, while the (325.3–192.0)-keV cascade is consistent with the QD1 calculation. The inset in Fig. 6(b) illustrates the quality of fitting the (191+192)-keV doublet.

The ^{145}Cs nucleus has larger deformation than lighter Cs isotopes [1]. In ^{141,143}Cs the positive-parity bands are of a decoupled character and the negative-parity levels, which are caused by octupole coupling, are elevated in energy (see Fig. 2 in Ref. [20]). In contrast, the positive-parity cascade in ^{145}Cs resembles a strongly coupled band. The negative-parity band most likely originates from the $h_{11/2}$ proton shell, which comes down in energy because of the onset of quadrupole deformation at $N = 90$. Such an assignment is supported by the alignment plot shown in Fig. 7. Using the spin assignments shown in Fig. 1 for the band on top of the 515.7-keV level, we obtain an aligned spin of $i = 5.5\hbar$ for this band, relative to the ground-state band of ^{146}Ba. This suggests that this band corresponds to the $\pi 1/2$ [550] proton subshell. Levels with spins 1/2, 3/2, and 5/2 of this band are elevated in energy and not populated in fission. We note that this band is similar to the analogous negative-parity band in the ^{147}La isotope [21].

The spin and parity assignment of $11/2^-$ for the 607.0-keV level and the angular correlation shown in Fig. 6 indicate a spin 9/2 for the 415.0-keV member of the ground-state band. However, such an assignment is in conflict with usual "spin counting" in bands populated in fission, where a monotonic increase of spins with increasing excitation energy is commonly observed. Following this rule and applying a spin of 3/2 for the ground state, one arrives at spin 11/2 for the 415.0-keV level. It is possible that the $\pi 1/2$ [420] and $\pi 3/2$ [422] configurations, which are very close to each other in ^{145}Cs [20], interact and produce a more complex ground-state band cascade, where spins do not increase regularly with excitation energy.

To obtain further insight into the structure of ^{145}Cs, we performed quasiparticle-rotor model calculations for this nucleus using the codes GAMPN, ASYRMO, and PROBAMO [22]. We used the deformation parameter $\epsilon_2 = 0.17$, in accordance with the predictions of Ref. [23], and the Coriolis attenuation parameter $\xi = 0.55$. Standard values for the κ and μ parameters of the ls and l^2 terms were used [24]. To calculate the γ-decay pattern, we used a collective g factor for the core of $g_R = Z/A$ and an effective value of the free neutron factor $g_s^{\mathrm{eff}} = g_s^{\mathrm{free}}$. More information on such calculations can be found in Refs. [25,26].

The results of the calculations are shown in Fig. 8. Calculated levels are normalized to the zero energy of the $3/2^+$ level, which has the dominant 3/2 [422] configuration. A good agreement between measured and calculated excitation energies for the negative-parity band in ^{145}Cs supports the $1/2^-$ [550] dominant proton configuration for the band starting at 515.7 keV.

Our calculations predict that the $1/2^+$ [420] and $3/2^+$ [422] proton configurations are close in energy to the ground state and, consequently, two $5/2^+$ levels will occur at low

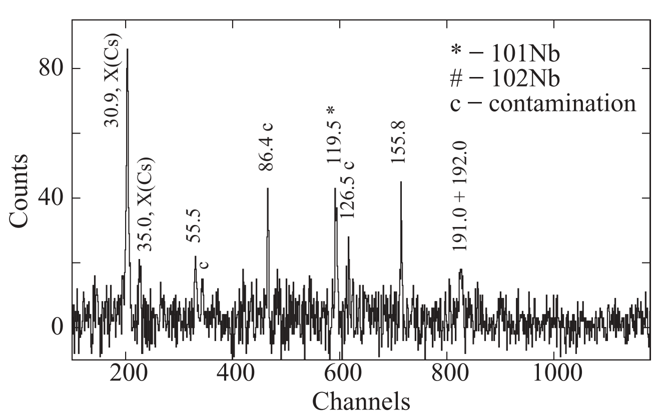

FIG. 5. LEPS spectrum double gated on 88.7- and 115.0-keV γ-ray lines in ^{145}Cs. Energies are labeled in keV. See text for further explanations.

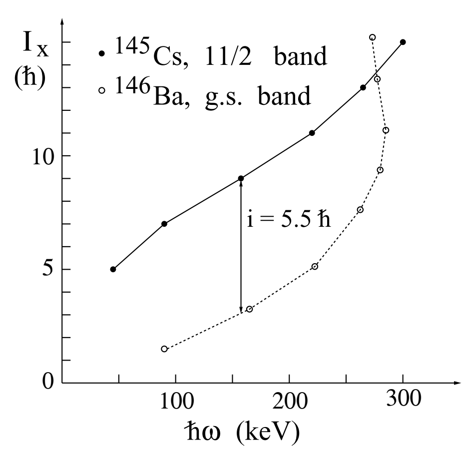

FIG. 7. Aligned angular momenta, I_x, of the negative-parity band in ^{145}Cs and the ground-state band of ^{146}Ba. Data for ^{146}Ba are from Ref. [4].

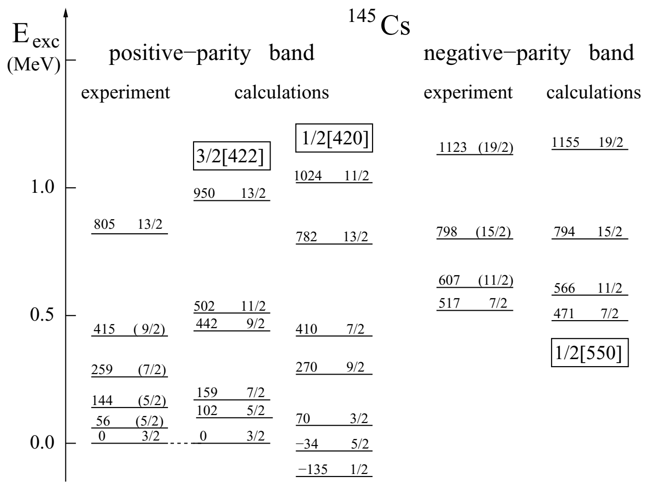

FIG. 8. Experimental and calculated excitation energies in ^{145}Cs. See text for further explanation.

energy. Therefore, it is possible to assign a spin of $7/2^+$ to the 259.2-keV level and a spin of $9/2^+$ to the 415.0-keV level, in agreement with the angular correlation data of Fig. 6. In Ref. [1] a magnetic moment, $\mu = 0.95(15)\mu_N$, was estimated for the 259.2- and 415.0-keV levels (the 203.8- and 359.4-keV levels in Ref. [1]), which agrees with the magnetic moment calculated for the $3/2^+$ [422] configuration [5] and measured for the ground state of ^{145}Cs [17].

The spin of $1/2^+$ calculated for the ground state is in conflict with the experimental measurement reported in Ref. [17]. We note, though, that the present calculations were performed assuming a reflection-symmetric shape. It was found in Ref. [20] that in a reflection-asymmetric potential the order of the $3/2^+$ [422] and $1/2^+$ [420] is reversed by the octupole interaction (see Fig. 2(a) in Ref. [20]) and the $1/2^+$ [420] band is effectively elevated in energy. A small correction owing to octupole coupling would improve the agreement between experiment and calculations. Therefore, it is of interest to check the strength of octupole correlations in ^{145}Cs. According to the present spin and parity assignments, the 192.0-keV

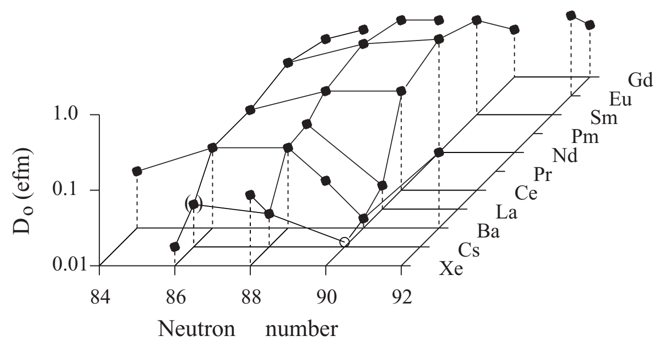

FIG. 9. D_0 moments in the neutron-rich lanthanides. The new value for ^{145}Cs is shown as an open circle. Other values are drawn using data from Ref. [8]. Lines are drawn to guide the eye.

transition in ^{145}Cs has an $E1$ multipolarity while the 91.2-keV transition is a stretched $E2$. One may, therefore, estimate the electric-dipole moment for the 607.0-keV level from γ-ray branching of the two transitions using the rotational formula $D_0 = \sqrt{5B(E1)/16B(E2)}Q_0$. The $B(E1)/B(E2)$ branching for the 607.0-keV level is $0.0050(8) \times 10^{-6}$ fm^{-2}. For the intrinsic electric-quadrupole moment we took $Q_0 = 3.3(7)$ b, an average of $Q_0 = 3.68(13)$ b for ^{146}Ba [27] and $Q_0 = 2.8(6)$ b for ^{144}Xe, extrapolated from Q_0 values for ^{140,142}Xe [9]. Using these values we obtained the intrinsic electric-dipole moment for ^{145}Cs of $D_0 = 0.013(4)$ efm.

The D_0 moment in ^{145}Cs is about two times smaller than in ^{143}Cs [8]. Figure 9 shows the D_0 values in neutron-rich lanthanides, including the new point for ^{145}Cs. It is possible that in ^{145}Cs there is a canceling of the D_0 moment similar to that observed in the ^{146}Ba and ^{147}La isotopes [3,4,21]. Considering the tentative character of the D_0 value in ^{145}Cs, this proposition still needs to be confirmed.

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