Revised spin values of the 991 keV and 1599 keV levels in ^{140}Sm

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The previously accepted spin values of the 991 and 1599 keV levels in ^{140}Sm have been revised and established as 2^+ and $0^{(+)}$, respectively. The γ-γ angular correlation method was used to determine the new spin values. The excited low-spin levels in ^{140}Sm were populated in the ^{140}Eu$\rightarrow$^{140}Sm and ^{140}Gd$\rightarrow$ ^{140}Eu$\rightarrow$^{140}Sm decays. The ^{140}Gd and ^{140}Eu nuclei were produced in the ^{112}Cd + ^{32}S reaction at a beam energy of 155 MeV.

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I. INTRODUCTION

The $^{140}_{62}$Sm$_{78}$ nucleus belongs to a transitional region where the nuclear shape changes rapidly with neutron number from a spherical shape at the $N = 82$ shell closure to a relatively large deformation for the most neutron-deficient Sm isotopes at neutron mid-shell. Relativistic mean-field calculations predict small oblate deformation for the $N = 78$ isotones ^{138}Nd, ^{140}Sm, ^{142}Gd, and ^{144}Dy, and rapidly increasing prolate deformation for the more neutron-deficient nuclei with $N < 78$ [1]. Woods-Saxon [2], relativistic Hartree-Fock-Bogoliubov (HFB) [3], and HFB calculations with the Gogny D1S interaction [4], which consider also the triaxial degree of freedom, predict ^{138}Sm and ^{140}Sm to be γ-soft. The observation of two almost degenerate isomeric 10^+ states with the $(\pi h_{11/2})^2$ and $(\nu h_{11/2})^{-2}$ configuration and the properties of the rotational bands on top of these isomers suggest prolate-oblate shape coexistence in ^{140}Sm above 3 MeV excitation energy [5]. A γ-ray spectroscopy experiment following the β decay of ^{140}Eu reported a low-lying 2^+ state in ^{140}Sm at 991 keV and a 3^+ state at 1598 keV, which were interpreted as members of a γ-vibrational band, supporting the notion of strong triaxiality for ^{140}Sm [2]. The spin assignments for the 2^+ and 3^+ states in this work were tentative and based on systematics [2]. A similar subsequent β-decay experiment tentatively assigned spin-parity $I^\pi = (0^+)$ to the state at 991 keV and $I^\pi = (2^+)$ to the state at 1599 keV [6], which entered the literature as the adopted spin values [7].

A low-lying 0^+ state as low as 991 keV excitation energy may be considered as an indication of shape coexistence also near the ground state. More information about the shape of ^{140}Sm near the ground state can be expected from a recent Coulomb excitation experiment [8] with the radioactive beam at the CERN on-line isotope mass separator ISOLDE [9]. However, the uncertainty in the spin assignment, in particular for the state at 991 keV, hampers the extraction of electromagnetic matrix elements from the Coulomb excitation data and makes the results ambiguous. To obtain unique information about the spin value of the level of interest, a complementary experiment was performed to measure the angular correlation of photons emitted from the excited states of ^{140}Sm. Preliminary results of the Coulomb excitation and γ-γ angular correlation experiments are reported in Ref. [8]. In the present work the γ-γ angular correlation experiment is described in detail.

II. EXPERIMENTAL DETAILS

The low-lying and low-spin states in ^{140}Sm (see Fig. 1) were studied via detection of the γ rays accompanying the β^+/electron-capture decay of ^{140}Eu$\rightarrow$^{140}Sm and ^{140}Gd$\rightarrow$^{140}Eu$\rightarrow$^{140}Sm. The ^{140}Eu ($T_{1/2} = 1.5$ s) and ^{140}Gd ($T_{1/2} = 15.8$ s) nuclei were produced in the ^{112}Cd + ^{32}S fusion-evaporation reaction at a beam energy of 155 MeV. The ^{32}S beam was delivered by the U-200P cyclotron [10] at the Heavy Ion Laboratory of the University of Warsaw.

The self-supporting ^{112}Cd target (with 97.3% enrichment) was rolled to a thickness of 3.6 mg/cm^2. A 5 mg/cm^2 thick gold foil was placed behind the target to stop the recoils in the center of the EAGLE [11] detector array, which at the time of the experiment consisted of 11 Compton-suppressed high-purity (HP) Ge detectors mounted at a distance of about 20 cm from the target. The ion beam had a time macrostructure with alternating 2 ms long beam-on periods followed by 4 ms long beam-off periods.

The γ radiation accompanying the β decays was measured during the off-beam periods to collect coincidence and singles spectra. By measuring the γ radiation only during the off-beam periods it was possible to suppress prompt radiation following the fusion-evaporation reactions and select only γ rays accompanying the β decay of the reaction residues. A total of about 10^7 coincidence events were registered during the off-beam periods. In addition to the γ-γ coincidence data, down-scaled singles spectra were recorded to monitor the detection efficiency of the individual detectors. The efficiency was additionally determined using standard procedures with

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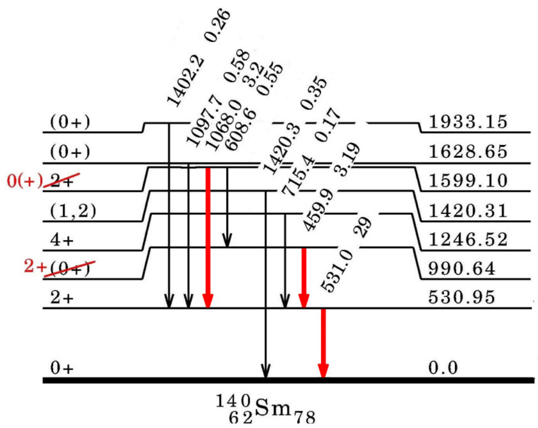

FIG. 1. (Color online) Partial level scheme of the ^{140}Sm nucleus relevant to our work taken from Ref. [7]. Spin values of the 991 and 1599 keV levels are shown according to our results. The crossed spin values are suggested in Refs. [6,7] but disagree with our results. The 352 keV transition (between the 1599 and 1247 keV levels) was removed from the level scheme presented in Ref. [6]; see text. Red thick arrows indicate γ transitions studied in this work.

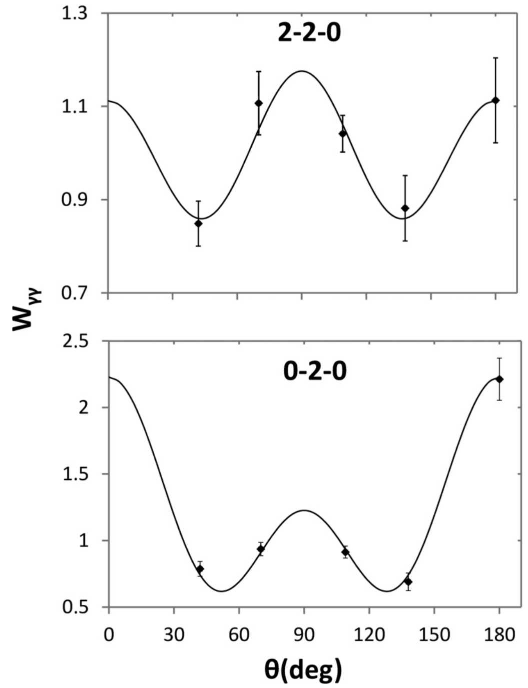

FIG. 2. γ-γ angular correlation for the 2-2-0 and 0-2-0 cascades. The experimental points and the best fit of Eq. (1) are shown.

calibration sources. The relative angles θ between the Ge detectors were as follows: 42°, 70°, 109°, 138°, and 180° and the number of detector pairs at each angle were 10, 17, 15, 9, and 4, respectively.

To compare the experimental results with the theoretical predictions of the γ-γ angular correlation for unoriented (random) sources [12,13] the standard formula

$$W_{\gamma\gamma} = A_{00}\big[1 + Q_2^{\text{det.1}}(E_{\gamma_1})Q_2^{\text{det.2}}(E_{\gamma_2})A_{22}P_2(\cos\theta) + Q_4^{\text{det.1}}(E_{\gamma_1})Q_4^{\text{det.2}}(E_{\gamma_2})A_{44}P_4(\cos\theta)\big] \quad (1)$$

was used, where A_{00} is a normalization factor, A_{22} and A_{44} are the angular correlation coefficients, Q_2 and Q_4 are solid-angle correction factors for detectors 1 and 2, and $P_2(\cos\theta)$ and $P_4(\cos\theta)$ are Legendre polynomials.

The values of Q_k (for $k = 2$, 4) were calculated using the computer code given in Refs. [14,15]. Due to the relatively large target-detector distance (∼20 cm) the differences between the values of Q_k for the individual detectors were small. Therefore, the average values of $Q_2 = 0.990$ and $Q_4 = 0.967$ were accepted for all detectors during the analysis. The theoretical values of the A_{22} and A_{44} coefficients were taken from Refs. [12,13]. The experimental coefficients were obtained by fitting the angular correlation function of Eq. (1) to the experimental intensities, as shown in Fig. 2.

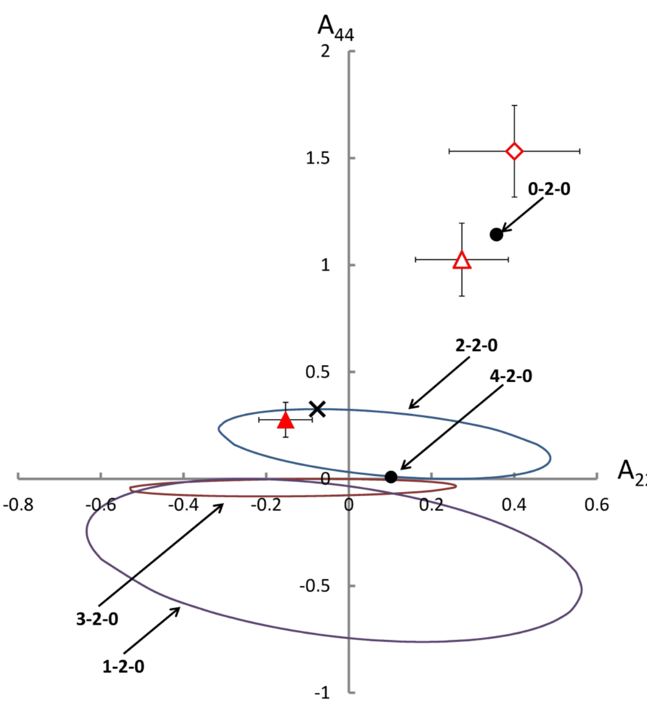

FIG. 3. (Color online) Parametric plot of the $A_{22}(\delta)$ and $A_{44}(\delta)$ angular correlation coefficients for the $I \to 2 \to 0$ cascades (for initial spin $I = 0,1,2,3,4$). Full circles indicate pure quadrupole $0 \to 2 \to 0$ and $4 \to 2 \to 0$ transitions. The cross on the 2-2-0 contour corresponds to the A_{22}, A_{44} coefficients for pure quadrupole ($\delta = \pm\infty$) transition. Full and open triangles indicate the experimental points for the 460–531/keV and 1068–531/keV cascades in ^{140}Sm, respectively. Open diamond indicates experimental point for the $0 \to 2 \to 0$ cascade in ^{140}Nd.

III. RESULTS

In this work the spin value of the 991 keV level (for the level scheme see Fig. 1) was determined by means of the γ-γ angular correlation of the 460 and 531/keV photons (see upper panel of Fig. 2). The resulting experimental values of the γ-γ angular correlation coefficients are $A_{22} = -0.15(7)$ and $A_{44} = 0.28(8)$ (see closed triangle in Fig. 3). These values indicate that (i) the spin of the 991 keV level is 2 instead of

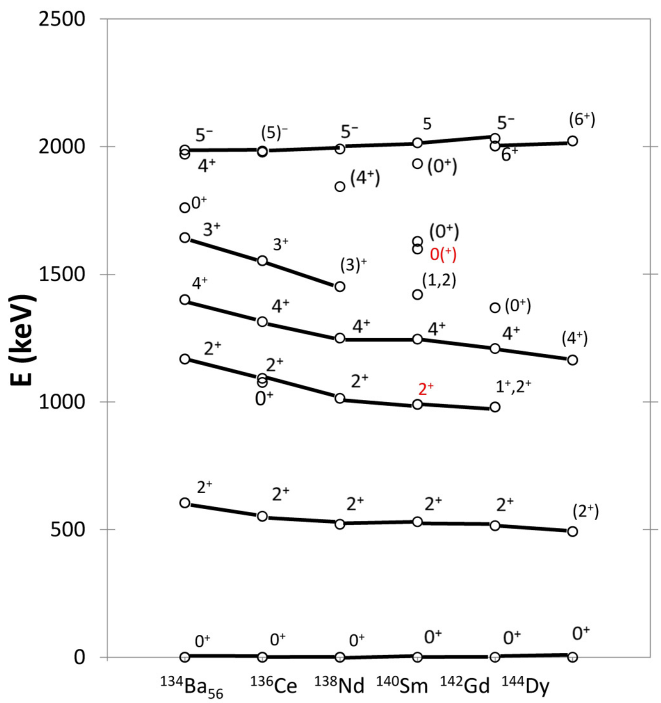

FIG. 4. (Color online) Systematics of the low-lying and low-spin states in even-even nuclei with $N = 78$ (^{134}Ba [16], ^{136}Ce [17], ^{138}Nd [18], ^{140}Sm [7], ^{142}Gd [19], ^{144}Dy [20]). Red (gray) numbers show spin values obtained in this experiment for ^{140}Sm.

(0^+) as given in Refs. [6,7], and (ii) the mixing ratio δ for the 460 keV transition equals 8^{+22}_{-4}.

The calculated correlation coefficients for the best experimental value of δ are $A_{22} = -0.162$ and $A_{44} = 0.322$, which agree well with the fitted values quoted above. Other possible spin values for the 991 keV level can be firmly rejected, since $I = 1$ or $I = 3$ would require negative A_{44}, whereas $I = 0$ or $I = 4$ would require positive A_{22}, as can be seen in Fig. 3.

The parity of the 991 keV level cannot be obtained from angular correlation experiments. Its value $\pi = +1$ can be deduced from the recent Coulomb excitation experiment [8] where the state at 991 keV was populated with similar intensity as the 4^+_1 state, which would be impossible for a negative-parity state that requires excitation via an $M2$ transition. An additional argument comes from the systematics (Fig. 4) of $N = 78$ isotones in the neighborhood of ^{140}Sm. A spin-parity of 2^+ for the 991 keV level in ^{140}Sm fits well with the systematics. Considering the information mentioned above one can firmly conclude that (i) the spin-parity of the 991 keV level is 2^+, and (ii) the multipolarity of the 460 keV transition is pure $E2$ or $E2$ with a small admixture of $M1$ $[(98^{+2}_{-4})\% E2 + (2^{+4}_{-2})\% M1]$.

The statistics in our experiment were sufficient to assign a spin also for the level at 1599 keV, which was populated with relatively strong intensity in the ^{140}Eu $\rightarrow$ ^{140}Sm decay (Fig. 1). Hence, the angular correlation of the 1068 and 531/keV photons could be studied. The experimental values $A_{22} = 0.27(11)$ and $A_{44} = 1.03(17)$ can be compared with the theoretical values [21] $A_{22} = 0.357$ and $A_{44} = 1.143$ for a 0-2-0 cascade. This clearly shows (see open triangle in Fig. 3) that the spin of the 1599 keV level is $I = 0$ instead of $I = 2$, as reported in Refs. [6,7], or $I = 3$, as suggested in Ref. [2]. All other spin values except $I = 0$ require much smaller or even negative coefficients A_{44} and can therefore be rejected.

The value of log $ft = 5.26$ [7] for the β^+ decay from the 1^+ ground state of ^{140}Eu to the 1599 keV level in ^{140}Sm indicates that the transition is allowed since log $ft \leqslant 5.9$, which suggests parity $\pi = +1$ for the level in question. This statement is weakened since the limit of the log ft value for allowed transitions could be smaller than 5.9 for nuclei at, or very near to, closed shells (see footnote on page iv of Ref. [22]). Therefore, the parity $\pi = +1$ of the 1599 keV level should be treated as a tentative value.

According to the level scheme given in Refs. [6,7] the 1599 keV level has a spin value equal to 2^+ and decays via three γ transitions with the following energies and multipolarities: 1068 keV ($E2/M1$), 609 keV ($E2$), and 352 keV ($E2$). Their intensities normalized to 100 parent decays were given as 3.2, 0.55, and 0.12, respectively [7]. Hence, taking into account the energies, multipolarities, and relative intensities of these lines the presence of the 352 keV transition was not in contradiction with the level scheme proposed in Refs. [6,7]. From the present experiment we know that the correct spin values of the 1599 and 991 keV levels are 0 and 2, respectively. In this case the 352 keV, $0 \rightarrow 4^+_1$ transition (electric or magnetic 2^4 pole) should have a partial half-life larger than 50 s [22]. The two competing $E2$ transitions of 1068 and 609 keV (see Fig. 1) are fast, since they are in coincidence with the 511 keV annihilation line accompanying the β^+ decay of ^{140}Eu. Taking into account these facts the intensity of the 352 keV line should be extremely low. This conclusion disagrees with the data from Refs. [6,7]. To solve this problem the coincidence intensity of the 352 keV line with the 715 keV, $4^+_1 \rightarrow 2^+_1$ line was measured and found to be at least one order of magnitude weaker than that reported in Refs. [6,7] (see Fig. 5). Therefore, one may summarize that if the discussed transition does exist, then it is located in another part of the ^{140}Sm level scheme. It is worth adding that in Ref. [6] the authors mentioned that the 352 keV line was placed in the decay scheme by energy sums.

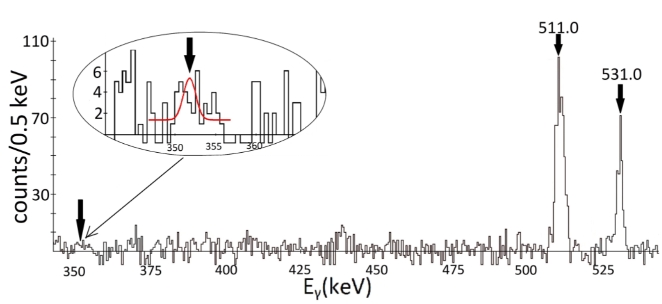

FIG. 5. (Color online) γ-γ coincidence spectrum obtained by gating on the 715 keV line (see Fig. 1). The arrows indicate 531 and 511/keV lines and the expected position of the 352 keV line. Insert: The part of the spectrum with the fitted Gaussian function based on the constant background.

To check the correctness of our analyses the angular correlation of the 640 and 774 keV photons accompanying the decay of the $0_2^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ cascade in ^{140}Nd [7] was measured. The 0_2^+ state was populated in the ^{140}Pm→ ^{140}Nd decay that is a part of the $A = 140$ decay chain initiated by ^{140}Gd produced in this experiment. The $A_{22} = 0.40(16)$ and $A_{44} = 1.53(21)$ angular correlation coefficients were obtained (see open diamond in Fig. 3). Comparing this experimental result with theoretical predictions one may conclude that only the sequence 0→2→0 is compatible with the data, in agreement with the spin values reported in Ref. [7]. The good agreement for ^{140}Nd gives confidence in the analysis technique and lends further support for the results obtained for ^{140}Sm.

IV. SUMMARY

In summary, the results of our γ-γ angular correlation measurements indicate that the spin of the 991 keV level is 2^+ [instead of the tentative value (0^+) quoted in Refs. [6,7]] and the spin of the 1599 keV level is $0^{(+)}$ instead of 2^+. The new spin assignment for the state at 991 keV is consistent with an interpretation of the state as the bandhead of a γ-vibrational band. Such a low-lying γ-vibrational band lends support to the calculations which predict ^{140}Sm to be γ-soft [3,4]. Furthermore, the new spin assignment has important consequences for the analysis of the Coulomb excitation data [8,23] taken at ISOLDE. In the case of the $0^{(+)}$ state at 1599 keV, its proximity to two other 0^+ states deserves attention. The result excludes the original assignment as the 3^+ member of the γ-vibrational band [2], which remains yet to be identified. It can be expected that more information about the nature of the excited 0^+ states and the missing 3^+ state will come from a planned Coulomb excitation experiment at the new high intensity energy (HIE) ISOLDE facility [24] which is currently under construction at CERN.

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