No evidence of reduced collectivity in Coulomb-excited Sn isotopes

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In a series of Coulomb excitation experiments the first excited 2^+ states in semimagic ^{112,116,118,120,122,124}Sn isotopes were excited using a ^{58}Ni beam at safe Coulomb energy. The $B(E2; 0^+ \to 2^+)$ values were determined with high precision (∼3%) relative to ^{58}Ni projectile excitation. These results disagree with previously reported $B(E2\uparrow)$ values [A. Jungclaus *et al.*, Phys. Lett. B **695**, 110 (2011).] extracted from Doppler-shift attenuation lifetime measurements, whereas the reported mass dependence of $B(E2\uparrow)$ values is very similar to a recent Coulomb excitation study [J. M. Allmond *et al.*, Phys. Rev. C **92**, 041303(R) (2015)]. The stable Sn isotopes, key nuclei in nuclear structure, show no evidence of reduced collectivity and we, thus, reconfirm the nonsymmetric behavior of reduced transition probabilities with respect to the midshell $A = 116$.

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A number of experimental and theoretical studies are currently focused on nuclear structure evolution far from the line of stability [1–3]. In particular, basic nuclear properties, e.g., the energy of the first excited 2^+ state and the reduced transition probabilities, i.e., $B(E2; 0^+ \to 2^+)$ or $B(E2\uparrow)$ values, along closed shells mark an area of great interest. Nuclei along closed proton or neutron shells are usually well reproduced by the generalized seniority scheme (see, e.g., Ref. [4]). The tin nuclei are of particular interest, because they form the longest isotopic chain between two doubly magic nuclei (^{100,132}Sn) which are accessible for nuclear structure studies.

One property of the even-A tin isotopes between the two doubly magic nuclei is the almost constant 2^+ excitation energies, which are well described by the seniority scheme. However, the predicted dependence of the $B(E2\uparrow)$ values between the two doubly magic nuclei has been shown to deviate from the experimental findings. The *a priori* expectation is a bell-shaped curve showing maximum collectivity at midshell. In recent years several experiments have found a different dependence. While the neutron-rich isotopes ($^{126-130}$Sn) smoothly decrease in collectivity, proton-rich nuclei are almost constant and are not mirror symmetric with respect to ^{116}Sn, as shown in Fig. 1. Most of the neutron-deficient nuclei were measured at radioactive isotope facilities [8–14], except for ^{112,114}Sn [15,16]. For the latter nuclei the $B(E2\uparrow)$ values were extracted relative to ^{116}Sn to obtain an accuracy of better than 3%. This normalization was however questioned based on recently performed Doppler-shift attenuation (DSA) measurements [5] which yield lower $B(E2\uparrow)$ values (up to 20%) as compared to earlier data reported in the literature [6].

Based on the recent experimental progress on the proton-rich side, a lot of efforts have been made to calculate the $B(E2\uparrow)$ values of the tin isotopes. Generally, large-scale shell model (LSSM) calculations yield quite satisfactory agreement for tin isotopes on the neutron-rich side, which are available for different employed inert cores [8,13,18]. The new experimental data [5] for stable Sn isotopes throw however a different light on this agreement. On the other hand, mean-field calculations like the relativistic quasiparticle random-phase approximation (RQRPA) [20,21] predict an asymmetric maximum around ^{106,108}Sn. For completeness a recent QRPA calculation [19] should be mentioned that, however, shows a good agreement with the experimental data.

To draw firm conclusions on the $B(E2\uparrow)$ pattern and to resolve the large experimental disagreements a series of Coulomb excitation experiments was conducted at the Inter University Accelerator Centre (IUAC) in New Delhi. Highly enriched targets (∼0.40–0.50 mg/cm^2) of ^{112,116,118,120,122,124}Sn were bombarded with ^{58}Ni ions at an incident energy of 175 MeV, which is well below the Coulomb barrier, to ensure pure electromagnetic interaction. In these experiments both projectile and target nuclei were excited and the excitation strength of the 2^+ state in ^{112,116,118,120,122,124}Sn was determined relative to the first excited 2^+ state in ^{58}Ni.

The scattered projectiles and recoils were detected in a newly developed annular gas-filled parallel-plate avalanche counter (PPAC) [22], subtending an angular range of $15^\circ \leqslant \vartheta_{\mathrm{lab}} \leqslant 45^\circ$ in the forward direction. The detector was position sensitive in both the azimuthal and the polar angles. The azimuthal angle φ was obtained from the anode foil which was divided into 16 radial sections of 22.5° each. To measure the polar angle ϑ the cathode was patterned in concentric conductor rings, each 1 mm wide, with an insulating gap of 0.5 mm between them, which resulted in an approximate

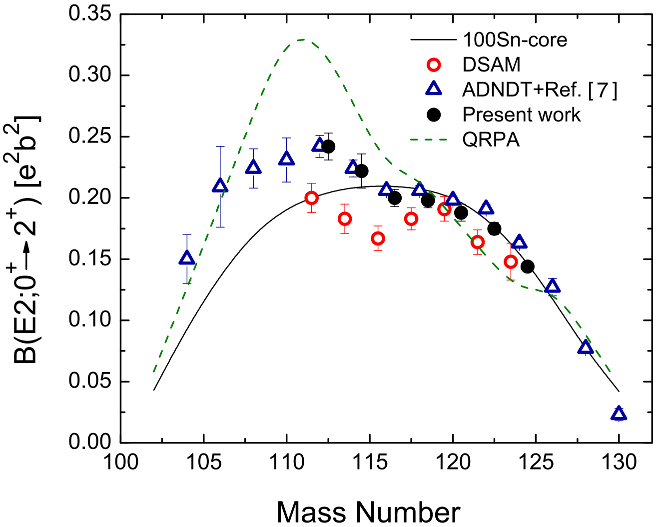

FIG. 1. Dependence of $B(E2\uparrow)$ values of Sn isotopes on the mass number. Surprisingly, one observes for the stable Sn isotopes a disagreement of up to ~20% between the recently measured values by Jungclaus *et al.* [5], using the DSA method, and the tabulated ADNDT data [6] including more recent data [7]. For comparison with the experimental data [8–18], the results of large-scale shell model calculation using the ^{100}Sn core [8] and the quasiparticle random-phase approximation [19] are shown.

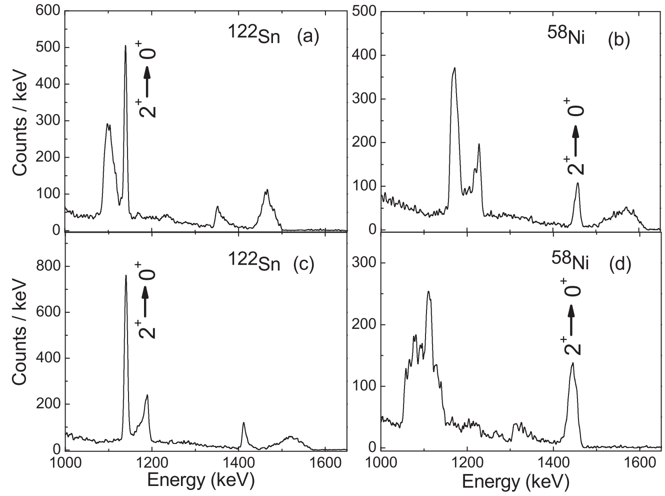

FIG. 2. Doppler-shift-corrected γ-ray spectra emitted from the ^{122}Sn target nuclei and the ^{58}Ni projectiles in the reaction ^{122}Sn(^{58}Ni,^{58}Ni*)^{122}Sn* at 175 MeV. In the top row the distant collision results ($22.1^\circ \leqslant \vartheta_{\rm cm} \leqslant 64.6^\circ$, ^{58}Ni detected in PPAC) are displayed for ^{122}Sn Doppler-corrected spectra (a) and ^{58}Ni corrected spectra (b) while the close collision results ($90^\circ \leqslant \vartheta_{\rm cm} \leqslant 150^\circ$, ^{122}Sn detected in PPAC) are shown in the bottom row for ^{122}Sn corrected spectra (c) and ^{58}Ni corrected spectra (d), respectively.

angular resolution of $\Delta\vartheta_{\rm lab} \sim 0.3^\circ$. Each ring was connected to its neighbor by a delay line of 2 ns. The cathode signals were read out from the innermost and outermost rings, and the $\tan\vartheta$ information was derived from the time difference of the delayed cathode and the prompt anode signals. An entrance window of 2-μm-thick Mylar foil was used for the PPAC. The detector was operated in an isobutane gas environment at ~10 mbar pressure. The noninteracting beam could leave the scattering chamber through a central hole in the PPAC with a diameter of 20 mm. Ni projectiles and Sn ejectiles could not be distinguished using the PPAC, but they belonged to different scattering regions (e.g., $22.1^\circ \leqslant \vartheta_{\rm cm} \leqslant 64.6^\circ$, ^{58}Ni detected in PPAC, and $90^\circ \leqslant \vartheta_{\rm cm} \leqslant 150^\circ$, Sn detected in PPAC), which are essential for the Doppler correction.

The deexcitation γ rays were measured in four Clover detectors mounted in the backward direction at $\vartheta_\gamma \sim 145^\circ$ with respect to the beam direction. The φ_γ angles for the Clover detectors were $\pm 45^\circ$ and $\pm 145^\circ$ with respect to the vertical direction. Individual energies and timing signals of the 16 Ge crystals of the four Clover detectors were recorded in coincidence with the PPAC anode and cathode signals on an event-by-event basis. Low-energy radiations were suppressed using Cu, Sn, and Pb absorbers of thickness between 0.5 and 0.7 mm placed in front of the Clover detectors. Energy calibrations and relative efficiency measurements were carried out using a ^{152}Eu source.

Although the projectile and target scatterings were not discriminated by the measured PPAC scattering angles, the particle position measurement allowed for a precise Doppler correction of the measured γ-ray energies. From the measured (ϑ,φ) angle and the assumption of a detected Ni or Sn nucleus, the velocities of both reaction partners and the recoil angles could be calculated from the two particle kinematics. Therefore, Doppler-corrected γ-ray spectra for distant and close collisions could be generated and are displayed in Fig. 2.

From the intensity of the Doppler-corrected γ-ray lines corresponding to the $2^+ \rightarrow 0^+$ transitions, the target as well as the projectile excitation could be extracted for distant collisions. These γ-ray yields are a direct measure of the $B(E2;\,0^+ \rightarrow 2^+)$ values and show almost no feeding from higher excited states. To obtain high-precision results, the $B(E2\uparrow)$ values of ^{112,116,118,120,122,124}Sn were determined relative to the $B(E2;\,0^+ \rightarrow 2^+) = 0.0650(12)\ e^2\mathrm{b}^2$ value of ^{58}Ni [6]. The experimental γ-ray ratios were corrected for the different Ge detector efficiencies (<1.2%) and target enrichment (<4.2%).

The Coulomb excitation calculations were performed using the Winther-de Boer COULEX code [23]. In these calculations, not only the first excited 2^+ state and the related $B(E2;\,0^+ \rightarrow 2^+)$ value was included but also the higher excited 2^+ and 4^+ states. The slowing down of the projectiles in the targets (0.8 %), the uncertainty of the PPAC boundaries (0.5 %), and the adopted ^{58}Ni $B(E2\uparrow)$ value (1.8%) were also considered. The subsequent γ-ray decay was calculated for the the particle-γ angular correlation, taking into account the internal conversion and the finite geometry of the γ detector. The deorientation of the particle-γ correlation, caused by the interaction of the nucleus with the magnetic moment of the atomic shell, was determined experimentally. For the short-lived 2^+ states ($T_{1/2} < 1$ ps) of tin isotopes the deorientation is expected to be very small. Because the tin ionization was not investigated in the present experiment and hence the atomic spin is unknown, the nuclear g factor of the 2^+ state was not extracted from deorientation coefficients as done in Ref. [7].

Our obtained $B(E2\uparrow)$ values (as given in Table I) agree well with the recent Coulomb excitation results, thus confirming the

TABLE I. Comparison of the measured $B(E2\uparrow)$ values of the Sn isotopes extracted from the present experiment with the Coulomb excitation experiment [7] and the DSA lifetime measurements [5]. The ratio of the tin $B(E2\uparrow)$ values to the $B(E2\uparrow)$ value of ^{58}Ni are also given.

Isotope	$B(E2\uparrow)_{\mathrm{Sn}}/B(E2\uparrow)_{\mathrm{Ni}}$ Present	$B(E2;0^+\rightarrow 2^+)$ Present	$B(E2;0^+\rightarrow 2^+)$ Ref. [7]	$B(E2;0^+\rightarrow 2^+)$ Ref. [5]
^{112}Sn	3.72(16)	0.242(11)	0.250(10)	0.200(12)
^{114}Sn	–	0.222(14)[a]	0.229(9)	0.183(12)
^{116}Sn	3.08(9)	0.200(7)	0.205(8)	0.167(10)
^{118}Sn	3.05(7)	0.198(6)	0.203(9)	0.183(9)
^{120}Sn	2.90(9)	0.188(7)	0.210(9)	0.191(10)
^{122}Sn	2.70(6)	0.175(5)	0.198(9)	0.164(10)
^{124}Sn	2.22(5)	0.144(4)	0.165(7)	0.148(15)

[a]The $B(E2\uparrow)$ value of ^{114}Sn [16] was normalized with respect to the average value determined from the present measurement.

disagreement with the DSA lifetime data. We confirmed earlier Coulomb excitation data from Refs. [24,25] and the adopted values from Ref. [6]. We note that with the present remeasurement for the $B(E2)$ values of ^{116}Sn, our previously published values of 0.242(8) e^2b^2 and 0.232(8) e^2b^2 for ^{112,114}Sn, which are based on a relative measurement, are unchanged for ^{112}Sn and decreased by ∼4.5% to 0.222(14) e^2b^2 for ^{114}Sn, respectively.

Because the experimental $B(E2\uparrow)$ values of the stable Sn isotopes show no evidence of reduced collectivity, the discussion reported in Kumar *et al.* [15] is still valid in which the experimental data are compared with theoretical calculations using the LSSM [8] and the RQRPA [20,21]. The dependence on the neutron number is asymmetric with respect to the midshell nucleus ^{116}Sn.

In summary, Coulomb excitation measurements have been performed for ^{112,116,118,120,122,124}Sn using ^{58}Ni projectiles. The determined $B(E2\uparrow)$ values were measured with high precision and agree well with earlier measurements as well as with recent Coulomb excitation experiments.

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[1] O. Sorlin *et al.*, Prog. Part. Nucl. Phys. **61**, 602 (2008).
[2] T. Faestermann *et al.*, Prog. Part. Nucl. Phys. **69**, 85 (2013).
[3] L. Coraggio, A. Covello, A. Gargano, N. Itaco, and T. T. S. Kuo, Phys. Rev. C **91**, 041301 (2015).
[4] I. Talmi, Nucl. Phys. A **172**, 1 (1971).
[5] A. Jungclaus *et al.*, Phys. Lett. B **695**, 110 (2011).
[6] B. Pritychenko *et al.*, At. Data Nucl. Data Tables **107**, 1 (2016).
[7] J. M. Allmond, A. E. Stuchbery, A. Galindo-Uribarri, E. Padilla-Rodal, D. C. Radford, J. C. Batchelder, C. R. Bingham, M. E. Howard, J. F. Liang, B. Manning, S. D. Pain, N. J. Stone, R. L. Varner, and C. H. Yu, Phys. Rev. C **92**, 041303(R) (2015).
[8] A. Banu *et al.*, Phys. Rev. C **72**, 061305(R) (2005).
[9] D. C. Radford *et al.*, Nucl. Phys. A **746**, 83 (2004).
[10] J. Cederkäll *et al.*, Phys. Rev. Lett. **98**, 172501 (2007).
[11] C. Vaman *et al.*, Phys. Rev. Lett. **99**, 162501 (2007).
[12] A. Ekström *et al.*, Phys. Rev. Lett. **101**, 012502 (2008).
[13] G. Guastalla *et al.*, Phys. Rev. Lett. **110**, 172501 (2013).
[14] P. Doornenbal *et al.*, Phys. Rev. C **90**, 061302(R) (2014).
[15] R. Kumar, P. Doornenbal, A. Jhingan, R. K. Bhowmik, S. Muralithar, S. Appannababu, R. Garg, J. Gerl, M. Gorska, J. Kaur, I. Kojouharov, S. Mandal, S. Mukherjee, D. Siwal, A. Sharma, P. P. Singh, R. P. Singh, and H. J. Wollersheim, Phys. Rev. C **81**, 024306 (2010).
[16] P. Doornenbal, P. Reiter, H. Grawe, H. J. Wollersheim, P. Bednarczyk, L. Caceres, J. Cederkall, A. Ekstrom, J. Gerl, M. Gorska, A. Jhingan, I. Kojouharov, R. Kumar, W. Prokopowicz, H. Schaffner, and R. P. Singh, Phys. Rev. C **78**, 031303(R) (2008).
[17] J. M. Allmond, D. C. Radford, C. Baktash, J. C. Batchelder, A. Galindo-Uribarri, C. J. Gross, P. A. Hausladen, K. Lagergren, Y. Larochelle, E. Padilla-Rodal, and C. H. Yu, Phys. Rev. C **84**, 061303(R) (2011).
[18] T. Back, C. Qi, B. Cederwall, R. Liotta, F. Ghazi Moradi, A. Johnson, R. Wyss, and R. Wadsworth, Phys. Rev. C **87**, 031306(R) (2013).
[19] S. Përu and M. Martini *et al.*, Eur. Phys. J. A **50**, 88 (2014).
[20] A. Ansari, Phys. Lett. B **623**, 37 (2005).
[21] A. Ansari and P. Ring, Phys. Rev. C **74**, 054313 (2006).
[22] A. Jhingan, DAE-BRNS Symp. Nucl. Phys. **61**, 966 (2016).
[23] A. Winther and J. de Boer, *in Coulomb Excitation*, edited by K. Alder and A. Winther (Academic, New York, 1966).
[24] R. Graetzer, S. M. Cohick, and J. X. Saladin, Phys. Rev. C **12**, 1462 (1975).
[25] P. H. Stelson, F. K. McGowan, R. L. Robinson, and W. T. Milner, Phys. Rev. C **2**, 2015 (1970).