Evidence for reduced collectivity around the neutron mid-shell in the stable even-mass Sn isotopes from new lifetime measurements

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Abstract

Precise measurements of the lifetimes of the first excited $2^+$ states in the stable even-$A$ Sn isotopes $^{112-124}$Sn have been performed using the Doppler shift attenuation technique. For the isotopes $^{112}$Sn, $^{114}$Sn and $^{116}$Sn the E2 transition strengths deduced from the measured lifetimes are in disagreement with the previously reported values and indicate a shallow minimum at $N = 66$. The observed deviation from a maximum at mid-shell is attributed to the obstructive effect of the $s_{1/2}$ neutron orbital in generating collectivity when near the Fermi level.

Keywords: Lifetimes, Sn isotopes, Doppler shift attenuation technique

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The chain of semi-magic tin isotopes occupies an exceptional position in nuclear structure research. With the 33 experimentally accessible isotopes between the two double-magic cornerstones $^{100}$Sn and $^{132}$Sn, it allows for systematic and stringent tests of the validity of nuclear structure models across an entire span of a large major systematic and stringent tests of the validity of nuclear structure physics. Indeed, the energy of the first excited $2^+$ states, B($E2$; $0^+_1 \rightarrow 2^+_1$) (in the following abbreviated as $B(E2)$), as a function of the number of particles in this $j$-shell [4]. Some features of this simple seniority model remain effective even when it is generalized by considering several $j$ orbitals and more realistic interactions [4]. Because of the strong pairing correlations along the tin isotopic chain, it has long been considered as a good example for the approximate validity of the generalized seniority scheme. Indeed, the energy of the first excited $2^+$ state is near constant across the entire major $N = 50 – 82$ neutron shell and at least in its upper half the $B(E2)$ values decrease with increasing neutron number from the mid-shell nucleus $^{116}$Sn toward the $N = 82$ shell closure following a smooth parabolic behavior as described also by seniority truncated large scale shell model calculations [5, 6, 7].

In recent years, however, a series of experiments have examined the $E2$ strength in the Sn isotopes with $A = 106-114$, in the lower half of the major neutron shell [7, 8, 9, 10].

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In these studies on stable and neutron-deficient isotopes, an increase in E2 transition strengths has been observed between the mid-shell isotope $^{116}$Sn and its neighbor $^{114}$Sn, with the values then staying nearly constant within the experimental uncertainties down to $^{106}$Sn. This behavior contrasts with predictions from modern large-scale shell model calculations [7].

The measured E2 transition strengths in the stable even-A Sn isotopes are mainly based on Coulomb excitation experiments while information from direct lifetime measurements is scarce. We have measured the $2_1^+$ state lifetimes in all of the stable even-A Sn isotopes using the Doppler-shift attenuation (DSA) method in order to provide an independent evaluation of the observed discontinuity in the $B(E2)$ systematics between $^{114}$Sn and $^{116}$Sn.

Two new experiments, with virtually identical experimental setups, were performed at the UNILAC accelerator of the Gesellschaft für Schwerionenforschung (GSI). In addition, we have analyzed data obtained in a recent magnetic moment measurement [14] at the Australian National University (ANU). At GSI 4.0 MeV/u beams of $^{112,114,116}$Sn were used in the first run and a 3.8 MeV/u $^{122}$Sn beam was used in the second. Besides the lifetime measurement we were aiming to determine the magnetic moments of the $2_1^+$ states using the transient field technique (the magnetic moment results will be presented elsewhere [15]); the beam particles therefore impinged on multilayer targets consisting of 0.67 mg/cm$^2$ (0.66 mg/cm$^2$ in the $^{122}$Sn run) natural C, 10.8 (10.9) mg/cm$^2$ natural Gd, 1.0 (1.0) mg/cm$^2$ Ta and finally a 4.86 (5.23) mg/cm$^2$ Cu layer. A thick Ta foil was mounted behind the target to stop the beam. Four Si diodes (1cm x 1cm each) were placed 30 mm (27 mm) downstream above and below the beam axis to detect the forward scattered C target ions in the vertical angular ranges of $2^\circ$-$20^\circ$ and $23^\circ$-$38^\circ$. The γ rays emitted from the excited states populated in the Coulomb excitation of the Sn projectiles on the C target layer were detected in coincidence with the C ions in four EUROBALL cluster detectors positioned in a horizontal plane at angles of $\pm65^\circ$ and $\pm115^\circ$ with respect to the beam axis at a distance of 24 cm (22 cm) from the target. Each of the cluster detectors consists of seven individual Ge crystals, which for the lineshape analysis have been combined into groups according to their average polar angle with respect to the beam. For the lifetime determination the spectra obtained with the detectors positioned at $53^\circ$, $65^\circ$, $115^\circ$ and $127^\circ$ to the beam axis have been analyzed because at these angles the lineshapes are most sensitive to the lifetime value.

To analyze the observed Doppler-broadened lineshapes and extract the lifetime information we modified the LINESHAPE program package [16] in order to (i) evaluate the kinematics of the Coulomb excitation reaction, taking into account the non-cylindrical geometry of the particle detectors, (ii) take into account the structure of the multilayer targets, and (iii) include angular correlation effects. For the description of the slowing-down process the stopping powers of Ziegler et al. [17] were used. Since the experiments at GSI were performed at relatively high beam energies, additional excited states above the first $2^+$ states of interest were populated. Thus feeding into the $2_1^+$ state from the higher states, mainly from the $4_1^+$ and $3_1^+$ levels, has to be taken into account in the analysis of the lineshapes. For each isotope under study the feeding intensities were determined from the γ ray spectra taking into account angular correlation effects. This observed feeding, which amounts to 5-15% from the $4_1^+$ and 15-30% from the $3_1^+$ levels, respectively, has been included in the fits to the lineshapes of the $2_1^+ \to 0^+$ transitions. While the $4_1^+$ states are too long lived to show a significant Doppler shifted fraction, the $3_1^+$ states are shorter-lived and their lifetimes have been determined from the lineshapes of the $3_1^+ \to 2_1^+$ transitions.

For each transition of interest eight different experimental lineshapes corresponding to the combinations of the four γ-ray detection angles with the two pairs of Si detectors covering different angular ranges have been analyzed. As an example of the lineshape analysis, Fig. 1 shows the fits obtained for the $2_1^+ \to 0^+$ ground state transition in $^{114}$Sn in the spectra taken at $53^\circ$, $65^\circ$, $115^\circ$ and $127^\circ$ to the beam axis in coincidence with C ions detected in the inner pair of Si detectors. Note that the lineshapes obtained at symmetric angles in forward and backward direction, $65^\circ$/$115^\circ$ and $53^\circ$/$127^\circ$, are not perfectly symmetric due to the initial recoil velocity being more than 7% of the velocity of light; relativistic effects must be included in the fitting procedure.

To consider the uncertainties introduced by the feeding contributions for the $2_1^+$ state, the intensities of both the $4_1^+ \to 2_1^+$ as well as $3_1^+ \to 2_1^+$ feeding transitions were varied independently by $\pm20\%$ and the resulting variation of the deduced $2_1^+$ lifetime was added to the statistical error.

![Figure 1](image-url)
Final lifetime values were obtained as weighted means of the eight individual fit results. Uncertainties in the stopping power description of about 5% have been considered in the determination of the quoted error. The results obtained for both $\tau(3^+_2)$ and $\tau(2^+_1)$ in $^{112,114,116,122}$Sn from the two GSI experiments are summarized in Table 1. It is noteworthy that the lifetimes of the $3^+_2$ states in $^{116}$Sn and $^{122}$Sn determined in the present work are in good agreement with the literature values [20, 21].

To test the robustness of the lifetime results we performed a number of checks using $^{114}$Sn as an example. To test the importance of an exact knowledge of the thicknesses of the various target layers, the thickness of the Gd and Ta layers were varied independently by $\pm 0.5$ mg/cm$^2$. The obtained lifetime values were all within 0.01 ps with the best fits obtained for the nominal thicknesses. This observed independence of the fitted lifetime on the Gd and Ta thicknesses is expected since the decay of the $2^+_1$ state in most cases takes place well before recoiling Sn ion reaches the Gd-Ta interface. And whenever the $2^+_1$ state had been populated from the long-lived $4^+_1$ state it decays after the ion has been completely stopped in the Cu layer. This means that possible variations of the layer thicknesses have no influence on the obtained lifetimes.

In a second step we varied the region of the lineshape considered in the fit. Choosing only the region of largest Doppler shifts corresponds to selecting the highest recoil velocities and the first layer of the backing. However, no changes in the resulting lifetime values were found (variations within 0.01 ps) for many different widths and positions of the fit region. Finally, to check the influence of the choice of the stopping power used in the lineshape analysis on the resulting lifetime values the analysis was repeated by replacing the Ziegler stopping powers with those of Northcliffe-Schilling (NS) [18]. The resulting lifetimes were again within 0.01 ps which indicates that for Gd as stopping material and the large recoil velocities relevant in this analysis both parametrizations are very similar. For a more detailed discussion of the full analysis procedure we refer the reader to a forthcoming publication [19].

The ANU measurement used a 190-MeV $^{58}$Ni beam provided by the ANU 14UD Pelletron accelerator and Coulomb excited the natural Sn layer of a multilayer target (0.06 mg/cm$^2$ natural Pd, 0.73 mg/cm$^2$ natural Sn, 4.7 mg/cm$^2$ Fe, 2.07 mg/cm$^2$ In and 12.5 µm Cu). The γ rays de-exciting the first-excited $2^+_1$ states in the even $^{116-124}$Sn isotopes were observed by four Ge detectors placed at $\pm 65^\circ$ and $\pm 115^\circ$ with respect to the beam axis in coincidence with backscattered $^{58}$Ni ions. For further details concerning the experiment see Ref. [14]. The lineshapes of the $2^+_1 \rightarrow 0^+_1$ transitions were analyzed using the same approach as described above for the GSI data with the only difference that it is now the target ion which is Coulomb excited and not the projectile. Since only the first $2^+_1$ states were excited in this experiment, and therefore no feeding corrections need be applied in the lineshape analysis, the determination of $\tau(2^+_1)$ in $^{116}$Sn from the ANU data provides an independent check of the procedure used in the analysis of the GSI data, in particular of the side-feeding corrections. Fig. 2 shows the relevant part of the γ ray spectrum observed in the detectors positioned at $\pm 65^\circ$. For the overlapping lines corresponding to the $2^+_1 \rightarrow 0^+_1$ transitions in $^{122}$Sn and $^{124}$Sn we assumed a value of $\tau=1.29(8)$ ps for the $2^+_1$ state in $^{122}$Sn, as obtained from the GSI data (see Table 1), and then determined the $2^+_1$ lifetime in $^{124}$Sn to be $\tau=1.48(15)$ ps. Note that in the case of the ANU data, the use of Northcliffe-Schilling instead of Ziegler’s stopping powers leads to slightly worse descriptions of the lineshapes and a decrease of about 0.03-0.04 ps in the resulting lifetimes.

With the results summarized in Table 1, directly measured lifetime values for the $2^+_1$ states are now available for all stable even-$\Lambda$ Sn isotopes. Comparing the $B(E2)$ values derived from these lifetimes to the literature values [5, 12, 13] systematically lower values were found in all cases with the discrepancy being largest for $^{112}$Sn, $^{114}$Sn and $^{116}$Sn. We emphasize here the robustness of the new data, particularly for revealing systematic trends, and also the absolute values. In $^{116}$Sn, our present value of $B(E2)=0.168(7)$ e$^2$b$^2$, which is based on the two independent lifetime values obtained from the GSI and ANU data, is about 20% smaller than the adopted value of 0.209(6) e$^2$b$^2$ [5]. Also, for the $B(E2)$ in $^{112}$Sn and $^{114}$Sn the observed difference is of the order of 20% (see Table 1). However, remembering that the $B(E2)$ values in $^{112,114}$Sn have been deduced in Refs. [12, 13] relative to an adopted value for $^{116}$Sn, it is interesting to note that renormalization to our new $B(E2)$ value for $^{116}$Sn leads to values of $B(E2)=0.195(8)$ e$^2$b$^2$ and $B(E2)=0.186(8)$ e$^2$b$^2$ for $^{112}$Sn and $^{114}$Sn, respectively, which are then in excellent agreement with our values. Coming back to the conflict-

![Figure 2: Lineshape fits of the $2^+_1 \rightarrow 0^+_1$ transitions in $^{116,118,120,122}$Sn in the spectrum observed in the Ge detectors positioned at $\pm 65^\circ$. For the overlapping lines corresponding to the $2^+_1 \rightarrow 0^+_1$ transitions in $^{122}$Sn and $^{124}$Sn we assumed a value of $\tau=1.29(8)$ ps for the $2^+_1$ state in $^{122}$Sn, as obtained from the GSI data (see Table 1), and then determined the $2^+_1$ lifetime in $^{124}$Sn to be $\tau=1.48(15)$ ps. Note that in the case of the ANU data, the use of Northcliffe-Schilling instead of Ziegler’s stopping powers leads to slightly worse descriptions of the lineshapes and a decrease of about 0.03-0.04 ps in the resulting lifetimes.](image-url)
Table 1: Lifetimes of the $2^+$ and $3_1^+$ states and the $B(E2; 0^+_g \rightarrow 2^+_1)$ transition probabilities in $^{112-124}$Sn determined in the present work compared to the adopted literature values [5].

<table>
<thead>
<tr>
<th>nucleus</th>
<th>$E(2^+)$ (keV)</th>
<th>$\tau(3_1^+)$ (ps)</th>
<th>$\tau(2^+_1)$ (ps)</th>
<th>$B(E2; 0^+_g \rightarrow 2^+_1)$ (e²b²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{112}$Sn</td>
<td>1257</td>
<td>0.31(2)</td>
<td>0.65(4)</td>
<td>0.537(18)²</td>
</tr>
<tr>
<td>$^{114}$Sn</td>
<td>1300</td>
<td>0.52(3)</td>
<td>0.60(4)</td>
<td>0.474(16)³</td>
</tr>
<tr>
<td>$^{116}$Sn</td>
<td>1294</td>
<td>0.48(3)</td>
<td>0.66(4)</td>
<td>0.559(15)</td>
</tr>
<tr>
<td>$^{118}$Sn</td>
<td>1230</td>
<td>–</td>
<td>0.79(4)</td>
<td>0.695(27)</td>
</tr>
<tr>
<td>$^{120}$Sn</td>
<td>1171</td>
<td>–</td>
<td>0.97(5)</td>
<td>0.916(19)</td>
</tr>
<tr>
<td>$^{122}$Sn</td>
<td>1141</td>
<td>0.13(2)</td>
<td>1.29(8)</td>
<td>1.101(23)</td>
</tr>
<tr>
<td>$^{124}$Sn</td>
<td>1132</td>
<td>–</td>
<td>1.48(15)</td>
<td>1.324(32)</td>
</tr>
</tbody>
</table>

1previous values from [12, 13] renormalized to the new GSI results
2The more precise values from [13] are quoted here instead of $B(E2; 0^+_g \rightarrow 2^+_1)=0.240(14)$ e²b² and $\tau=0.544(32)$ ps [5].
3The more precise values from [12] are quoted here instead of $B(E2; 0^+_g \rightarrow 2^+_1)=0.245(4)$ e²b² and $\tau=0.48(10)$ ps [5].
4from Refs. [20] and [21]

ing case of $^{116}$Sn, it is interesting to note that the adopted $B(E2)$ value quoted in [5] is based on fifteen individual measurements (ranging from 0.145(21) to 0.29(6) e²b²) performed between 1957 and 2000 using Coulomb excitation, nuclear resonance fluorescence or electron scattering. While our new values deducted from the measured lifetimes overlap within the experimental uncertainties with eight of them, they clearly deviate from the values obtained in Coulomb excitation experiments, which have the smallest quoted error bars, namely 0.216(5) e²b², 0.195(7) e²b² and 0.223(13) e²b² [22, 23, 24], and which dominate the adopted value.

Unfortunately only in three cases, $^{112}$Sn, $^{114}$Sn and $^{120}$Sn, measurements of the $2^+_1$ lifetime using Doppler techniques have been reported in the literature. Using the (n,n’γ) reaction and the DSA method, Orcz et al. obtained a value of $\tau(2^+_1)=0.750^{(+125)}_{(-80)}$ ps in $^{112}$Sn which later on was corrected to $\tau(2^+_1)=0.535^{(+100)}_{(-80)}$ ps [10]. Note that, in contrast with the present DSA measurements, those in Ref. [10] have a very low recoil velocity and the measured average Doppler shift is relatively insensitive to nuclear lifetimes in this time regime. In $^{114}$Sn the Cologne group measured $\tau(2^+_1)=0.56(11)$ ps performing a DDCM (differential decay curve method) coincidence analysis of plunger data [25]. Finally, DSA values of $\tau(2^+_1)=0.45(15)$ ps for $^{114}$Sn and $\tau(2^+_1)=0.95(6)$ ps for $^{120}$Sn have been reported in Refs. [26, 27]. All these values agree within the experimental uncertainties with the results of our present work.

The experimental $B(E2)$ values in $^{112-124}$Sn obtained in the present work are compared to literature values in Fig. 3. While the adopted values are smoothly increasing from $^{124}$Sn towards the mid-shell nucleus $^{116}$Sn, our new results rather seem to indicate a minimum at $N=66$ followed by a smooth increase between $^{116}$Sn and $^{112}$Sn. It is important to remember that the new $B(E2)$ values for $^{112,114,116}$Sn and $^{116,118,120}$Sn, respectively, have been consistently determined under identical conditions in the GSI and ANU experiments. A similar behavior of the $E2$ strength in the upper half of the N=50-82 neutron shell, namely a maximum at $^{120}$Sn, has already been observed in a study using nuclear resonance fluorescence techniques [28].

As shown in Fig. 3, there is a very close matching between the observed minimum in transition strengths and the increase in $2^+_1$ excitation energies around $^{114,116}$Sn. From the theoretical point of view, the consistent description of nuclear properties such as the energy of the first excited $2^+$ state or the $B(E2; 0^+_g \rightarrow 2^+_1)$ transition probabilities across the entire span of a large major neutron shell is a very challenging task. In the nuclear shell model a neutron configuration space consisting of all five orbitals between $N=50$ and $N=82$, namely $d_{5/2}$, $g_{7/2}$, $s_{1/2}$, $d_{3/2}$ and $h_{11/2}$, is still far too big to be treated in an exact way. In the large-scale shell model calculations presented in Ref. [7], a truncation scheme based on the generalized seniority model was employed. The calculated $B(E2)$ values show a parabolic behavior with a maximum for the mid-shell nucleus $^{116}$Sn (see Fig. 3). More recently, however, expanded shell model calculations [11] have for the first time shown deviations from a $B(E2)$ symmetry around mid-shell. This interesting result certainly motivates further theoretical investigation. Besides the shell model calculations other theoretical approaches have recently been used to study the systematic behavior of $E2$ transition strengths in the Sn isotopes. The $2^+_1$ energies and $B(E2)$ transition probabilities for all Sn isotopes from N=50 to N=82 have been calculated in a relativistic quasiparticle random phase approximation (QRPA) [29, 30]. In these calculations, which are included in Fig. 3, the transition strength shows a maximum of about 0.24 e²b² around $^{106}$Sn/$^{108}$Sn, decreases with increasing neutron number towards mid-shell and then stays nearly constant around 0.15 e²b² up to $^{124}$Sn before it drops again towards $^{130}$Sn. Another example are the QRPA calculations of Terasaki [31] which unfortunately only have been performed for the upper half of the major shell. Here the
as reflected in the decrease of $N$ in the region this orbit is close to the Fermi level. The latter is the case below the Fermi level, it has marked consequences when excitations are excluded. Whereas this peculiarity is unimportant as long as the excitations are included, the detrimental role of the orbit plays a distinctive role since this orbit is either far above or far below the Fermi level in this region, and inhibits collectivity. While the new experimental results are in contrast to the seniority truncated large-scale shell model calculations, which predict a maximum of the $E2$ strength at $N = 66$ [7], expanded shell model calculations employing new interactions [11] indicate a shallow maximum around $N = 68 - 70$, closer to the experimental findings. New insight into the proton and neutron composition of the nuclear wave functions is awaited from the determination of the magnetic moments of the $2^+_1$ states from the same data set [15] which may elucidate the interplay between single particle and collective degrees of freedom.

We hope that our new experimental results for the stable Sn isotopes will stimulate new theoretical studies as well as new experiments to improve and extend the $B(E2)$ measurements on the neutron-deficient radioactive isotopes.

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