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Intermediate-energy Coulomb excitation of $^{104}\text{Sn}$: Moderate $E2$ strength decrease approaching $^{100}\text{Sn}$

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The reduced transition probability $B(E2)\uparrow$ of the first excited $2^+$ state in the nucleus $^{104}\text{Sn}$ was measured via Coulomb excitation in inverse kinematics at intermediate energies. A value of $0.173(28) e^2\text{fm}^4$ was extracted from the absolute cross section on a Pb target. Feeding contributions in $^{104}\text{Sn}$ from higher lying states were estimated by a reference measurement of the stable $^{112}\text{Sn}$. Corresponding only to a moderate decrease of excitation strength relative to the almost constant values observed in the proton-rich, even-$A$ $^{106-114}\text{Sn}$ isotopes, present state-of-the-art shell-model predictions, which include proton and neutron excitations across the $N = Z = 50$ shell closures as well as standard polarization charges, underestimate the experimental findings.

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Across the Segré chart of nuclei, the tin isotopes take an eminent position. Besides containing the longest chain of isotopes in between two doubly magic nuclei, in this case $^{100}\text{Sn}$ and $^{132}\text{Sn}$, accessible to nuclear structure research, the valley of stability against $\beta$ decay crosses this chain at midshell. This allows for systematic studies of basic nuclear properties from very proton-rich $N = Z$ to very neutron-rich nuclei. Of high interest in this context is the robustness of the proton $Z = 50$ shell closure when the $N = 50, 82$ magic numbers are approached. Experimentally, the $Z = 50$ correlated gap size can be inferred from mass measurements when data from neighboring isotones are available. The magnitude of the proton gap is well known for neutron-rich nuclei beyond the end of the major shell and shows a maximum for $^{132}\text{Sn}$ [1]. On the proton-rich side, however, experimental information is more scarce and only indirect evidence for a good $Z = 50$ shell closure exists, e.g., the large Gamov-Teller strength observed in the $\beta$ decay of $^{100}\text{Sn}$ [2].

Complementary shell evolution probes can be obtained from the $2^+_1 \rightarrow 0^+_gs$ transition energies, $E(2^+_1)$, and their respective reduced transition probabilities $B(E2; 0^+_gs \rightarrow 2^+_1)$, in short $B(E2)\uparrow$. While the $E(2^+_1)$ values of the tin isotopes between $^{100}\text{Sn}$ and $^{132}\text{Sn}$ are well established and exhibit only very little variation—the highest value is $1.472 \text{ MeV}$ for $^{100}\text{Sn}$, the lowest is $1.132 \text{ MeV}$ for $^{124}\text{Sn}$ [3,4]—the $B(E2)\uparrow$ transition strengths follow a different pattern. The a priori expectation is a curve showing maximum collectivity at midshell and smoothly decreasing towards the shell closures, reflecting the number of particles times the number of holes available within the major shell. This perception is put on a formal base for a single $j$ shell by the seniority scheme (see, e.g., Ref. [5]), which predicts constant $E(2^+_1)$ excitation energies and a parabolic pattern for the transition strengths. It has been shown that these key characteristics remain valid in the generalized seniority scheme as long as the orbits within the major shell are filled with the same rate, while for different level occupancies a shallow minimum for the $B(E2)\uparrow$ values can be obtained at midshell [6].

In recent years, several experimental findings generated large interest regarding the $E2$ strengths pattern in the tin isotopes. While the neutron-rich isotopes with $A = 126, 128, 130$ follow the anticipated trend of smoothly decreasing $B(E2)\uparrow$ values towards the major shell closure [7,8] well described by large-scale shell-model (LSSM) calculations [9,10], the proton-rich nuclei take a different path. Commencing with the stable $A = 114$ isotope a steadily growing deviation from the shell-model expectations was observed with almost constant $B(E2)\uparrow$ values for the $A = 106–112$ isotopes [9–14]. Conversely, the relativistic quasiparticle random phase

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approximation (RQRPA) calculations presented in Ref. [15] agree well for proton-rich nuclei but underestimate $B(E2)^{\uparrow}$ values for $A = 112–124$. This triggered a revisit of the stable tin isotopes via direct lifetime measurements, yielding generally lower $E2$ transition strengths than the adopted values given in Ref. [4] and even a local minimum for the midshell $A = 116$ nucleus [16].

While the $B(E2)^{\uparrow}$ value of $^{102}$Sn remains missing for a complete pattern of the tin isotopes within the major shell, a first attempt for $^{104}$Sn with limited statistics has recently been made [17]. The result of $0.10(4)\ e^2\text{b}^2$ indicates a steep decrease of excitation strength in agreement with LSSM calculations. In a second measurement, a considerably larger value of $0.180(37)\ e^2\text{b}^2$ was obtained [18]. In order to ameliorate the experimental situation, a new measurement of the $2^+\rightarrow 0^+$ transition strength in $^{104}$Sn is desirable. Here, we report on the first $B(E2)^{\uparrow}$ extraction in the unstable, proton-rich tin nuclei from absolute Coulomb excitation cross sections. Previously deduced values relied on target excitation at “safe” [10,11] and intermediate [12] energies or used an isotope with known excitation strength as normalization [9,17,18]. In fact, all reported values from intermediate-energy Coulomb excitation measurements above 100 MeV/nucleon rely on the latter method [9,19,20] and so far no attempt has been made to determine absolute cross sections at these high energies. Therefore, in the present work the stable $^{112}$Sn isotope, which has a known $B(E2)^{\uparrow}$ value, was Coulomb excited as well in order to validate the method.

The experiment was performed at the Radioactive Isotope Beam Factory, operated by the RIKEN Nishina Center and the Center for Nuclear Study of the University of Tokyo. A $^{124}$Xe primary beam was accelerated up to an energy of 345 MeV/nucleon and impinged on a 3-mm-thick Be production target at the F0 focus of the BigRIPS fragment separator [21]. The $Bp - \Delta E - Bp$ method was applied to select and purify secondary beams of $^{104}$Sn and $^{112}$Sn in two subsequent measurements. The beam cocktail compositions were identified event by event. An ionization chamber located at the focal point F7 measured the energy loss $\Delta E$, yielding the fragments’ element number $Z$. The combination of position and angle measurements at the achromatic focal point F3 and the dispersive focal point F5 with parallel plate avalanche counters (PPAC) [22] and a time-of-flight (TOF) measurement with two plastic scintillators placed at the focal points F3 and F7 enabled the deduction of the mass-to-charge ratio $A/Q$. For the $^{104,112}$Sn secondary beams, momentum acceptances were 2.2% and 0.9%, respectively.

The secondary beams were transported to the focal point F8, where a 557 mg/cm$^2$ thick Pb target was inserted to induce Coulomb excitation reactions. At midtarget, the secondary beam energies were 131 and 154 MeV/nucleon for the $^{104,112}$Sn fragments. In order to enhance the number of tin fragments in the fully stripped charge state, 6 mg/cm$^2$ thick aluminum foil was placed behind the reaction target. Scattering angles were determined with two PPACs located 1430 and 930 mm upstream and one PPAC located 890 mm downstream from the secondary target. The PPAC’s position resolution in $X$ and $Y$ was 1 mm ($\sigma$), allowing for a scattering angle reconstruction resolution of about 6 mrad, while an angular straggling of 6–8 mrad was calculated with the ATIMA code [23]. Grazing angles, calculated using the formulas given in Ref. [24], were 28 and 23 mrad for $^{104,112}$Sn and their respective energies in front of the reaction target. Due to the scattering angle resolution and the angular straggling, a cut on “safe” angles would have led to a loss of a large fraction of the $\gamma$-ray yield. Therefore, no angular cut was applied and contributions from nuclear excitations were determined from inelastic scattering on a 370 mg/cm$^2$ thick carbon target.

To detect $\gamma$ rays from the $2^+\rightarrow 0^+$ transitions, the reaction target was surrounded by the DALI2 array [25]. It consisted of 186 NaI(Tl) detectors, covering center-of-crystal angles from 19 to 150 deg. The efficiency of the DALI2 spectrometer was measured with $^{60}$Co and $^{88}$Y stationary sources and agreed within 5% to simulations using GEANT4 [26]. For the 1.33-MeV $\gamma$ ray emitted by the stationary $^{60}$Co source, a full energy peak (FEP) detection efficiency of 14% and an energy resolution of 6% (FWHM) were measured for the full array. Radiation arising from secondary bremsstrahlung produced from the ions’ deceleration in the reaction target was the anticipated main source of background. Therefore, the beam pipe at the F8 focus was enclosed by 1-mm lead and 1-mm tin shields. In addition, only forward-angle detectors in the rest frame were analyzed. After Doppler shift correction for a 1.26-MeV $\gamma$ ray emitted in flight, values of 10% and 8% (FWHM) were expected for the FEP efficiency and energy resolution, respectively.

Reaction products were identified behind the reaction target by the ZeroDegree spectrometer [21], using the previously described $\Delta E - Bp - TOF$ method from focus F8 to focus F11. Angular acceptances were $\pm 30$ mrad vertically and $\pm 45$ mrad horizontally for particles passing ZeroDegree with the central momentum. Figure 1 displays the particle identification plot for the $^{104}$Sn setting, which exhibits three charge states. Including efficiencies of 83 and 76% for scattering angle determination, 180 and 920 particles per second of $^{104,112}$Sn ejectiles were detected in the ZeroDegree spectrometer in their fully stripped charge state. Figure 2 displays the $\gamma$-ray spectra measured in coincidence with fully stripped $^{104,112}$Sn ions detected in BigRIPS and ZeroDegree after applying the
sections on carbon were reproduced with the DWEIKO code. The density presented in Ref. [30]. The experimental cross sections on top of two exponentials for the background (blue dotted line) shapes with simulated response functions (red dotted line). Intensities were determined by fitting the observed line shapes with simulated response functions (red dotted line) on top of two exponentials for the background (blue dotted line). The resulting curves are shown by the solid lines.

Doppler shift correction. The two transitions were observed at 1258(6) and 1257(6) keV, close to the literature values of 1260 and 1257 keV [4]. The intensities were determined by fitting the experimentally observed spectra with simulated response functions on top of two exponentials for the background.

Measured inelastic cross sections $\sigma_{\text{exc}}$ are composed of contributions from nuclear excitation ($\sigma_N$), Coulomb excitation to the $2^+_1$ state ($\sigma_C$), and feeding from Coulomb excitation of higher lying states ($\sigma_f$). Thus, a measured cross section on the Pb target can be converted to a $B(E2|1^+)$ value only if $\sigma_N$ and $\sigma_f$ are quantified. In addition, the ZeroDegree angular acceptance depends on the momentum distribution of the secondary beam and has to be corrected for. For the inelastic scattering of the $^{104,112}\text{Sn}$ isotopes on the carbon target, cross sections to the $2^+_1$ state of 28(3) and 46(4) mbar·sr were measured, which include feeding contributions. Here, it is sufficient to determine the nuclear contributions yielding an “effective” deformation length & that can be applied in calculations of $\sigma_n$ for the lead target, assuming that the nuclear excitation patterns are similar. In order to extract & optical potentials, and deformation lengths of $\delta = 0.32(2)$ and 0.44(3) fm for $^{104,112}\text{Sn}$. For inelastic scattering of $^{112}\text{Sn}$ on the Pb target, the cross section to the $2^+_1$ state was $\sigma_{2^+_1} = 479(37)$ mbar, while a cross section of $\sigma_n + \sigma_f = 395(21)$ mbar was expected from DWEIKO calculations. The errors included in the expectation value originated from the $B(E2|1^+)$ value of 0.242(8) e$b^2$ [4,14] (13 mbar), the derived “effective” deformation length (5 mbar), the angular transmission shown in Fig. 3(a) (8 mbar), as well as approximations made in the numerical calculations (14 mbar). Comparisons to the calculated values of Refs. [32,33] made with different codes showed agreement within on average 4%, motivating the latter error on the calculations. From the difference between measured cross section and the expectation value, a feeding contribution of $\sigma_f = 84(43)$ mbar was determined. Measured and deduced cross sections are summarized in Table I.

Feeding can be attributed to single-step Coulomb excitations to higher lying states and subsequent decay via the $2^+_1$ state.
state, while multistep excitations play only a minor role at intermediate energies. For example, the $B(E3)$ value to the $3^{-}_1$ state at 2355 keV in $^{112}$Sn has a strength of 0.087(12) $e^2b^3$ [34] and decays through the $2^+_1$ state. This translates to a feeding contribution of 10(2) mbarn. For $E2$ excitations, the total strength measured in the heavier $^{116-124}$Sn isotopes between 2 and 4 MeV corresponds to about 10% of that to the first excited state [35], while no experimental information is available for $2^+$ states at higher energies. Figure 3(c) displays the measured differential cross section as function of scattering angle for $^{112}$Sn. It is compared to the calculated nuclear cross section, the $2^+_1$ Coulomb excitation cross section, their combination, and adding the feeding from the $3^+_1$ and $2^+_2$ states. For the latter, the feeding was adjusted to match the experimental cross section. Coulomb excitations are dominant for all scattering angles, as nuclear contributions are sizable only around the grazing angle. A larger nuclear contribution would have resulted in a maximum at the grazing angle. Additionally, only by including sizable feeding can the curve up to scattering angles of $\approx 20$ mrad be reproduced. All calculations were convoluted with the detector resolution, the angular straggling, and the observed ZeroDegree scattering angle transmission.

The observed feeding contributions in $^{112}$Sn can be used to evaluate the feeding for $^{104}$Sn. We follow a similar approach to the one presented in Ref. [36] for neutron-rich magnesium isotopes to determine its value. In a simple picture, feeding originates from the $3^+_1$ excitation and fragmentation of the $E2$ excitation strength to many $2^+$ states between 2 MeV and the proton separation energy $S_p$ (7.554(5) MeV for $^{112}$Sn and 4.286(11) MeV for $^{104}$Sn [1]). Assuming an uniform $E2$ excitation strength distribution in this region and the same $E3$ excitation strength, correcting for the angular transmission shown in Fig. 3(b) results in a feeding of $\sigma_f = 41(21)$ mbarn for $^{104}$Sn, mainly due to the lower $S_p$ value. This estimation may be corroborated by a higher peak-to-background ratio for $^{104}$Sn despite a lower total cross section, showing that fewer high lying excited states are populated.

For inelastic scattering of $^{104}$Sn on the Pb target, a cross section of $\sigma_{2^+_1} = 289(30)$ mbarn was measured. Taking the previously determined nuclear contributions and the feeding into account, a $B(E2)$ value of 0.173(28) $e^2b^2$ was deduced. Note that due to the lower beam energy and the reduced scattering angle acceptance, nuclear contributions were significantly suppressed, as can be seen in the differential cross section in Fig. 3(d). The new $B(E2)$ value is displayed in Fig. 4 together with known data in between the two doubly magic tin nuclei. It is noteworthy that extracted $B(E2)$ values from the present experiment are robust against applying scattering angle cuts, as shown in the inset of Fig. 4. Systematic and statistical errors are shown individually by the hatched areas. See text for details.

![Fig. 4](image-url)
parabola in agreement with the neutron-rich nuclei but fail to reproduce the \( B(E2) \) enhancement for proton-rich nuclei.

In the most recent shell-model calculation, denoted LSSM in Fig. 4, the calculations were expanded to a \(^{90}\text{Zr}\) core and a \( gd \) model space, thereby allowing neutron as well as proton excitations across the \( N = Z = 50 \) gap \cite{17}. The standard effective charges were used and truncation was applied depending on the nucleus’s neutron number due to computational limits. However, the inclusion of neutron excitations across the \( N = 50 \) gap augmented the \( B(E2) \) values only slightly. For \(^{104}\text{Sn}\), a value of about 0.1 \( e^2b^2 \) is predicted, well below our experimental finding, and also the experimental \( B(E2) \) for \(^{108}\text{Sn} \) are underestimated.

Different suggestions to break the symmetry in the theoretical \( B(E2) \) pattern have been made ranging from refined tuning of the proton-neutron monopoles \cite{9,11}, inclusion of excitation across the \( N = 50 \) shell \cite{9}, a \( N = 50 \) shell gap reduction \cite{10}, to simply using two different sets of single-particle levels and effective charges for the lower and upper half of the shell \cite{37}. In an alternative approach that included the neutron \( gd \) and \( \hbar \ell_{11/2} \) orbitals as model space and single-particle energies fitted to experimental data \cite{40}, isospin-dependent effective charges as proposed by Bohr and Mottelson \cite{41} were introduced into the calculations \cite{38}. The neglect of proton excitations was compensated by normalizing the effective charges to \( e_V = 1.0e \) in the middle of the shell for \(^{116}\text{Sn} \), resulting in \( e_V > 1.0e \) \( (e_V < 1.0e) \) in the lower (upper) half of the shell. Indeed, a good overall agreement is observed and nuclear excitation on a low-energy target. Such an approach allows for the use of very thick reaction targets and thus gives access to more exotic nuclei.

In summary, a \( B(E2) \) value of 0.173(28) \( e^2b^2 \) was measured for \(^{104}\text{Sn} \) in intermediate-energy Coulomb excitation. The drop in excitation strength is much smoother than obtained in Ref. \cite{17} and cannot be reproduced by present LSSM calculations using standard effective charges as well as proton and neutron excitation across the \( N = Z = 50 \) shell. Moreover, it was demonstrated that given the significant scattering angle resolution and angular straggling at energies well above 100 MeV/nucleon, nuclear excitation should be explicitly taken into account in \( B(E2) \) determinations rather than suppressed in an inaccurate angular cut. Feeding from higher lying states cannot be neglected but can be determined from known \( B(E2) \) values. A simple scaling of measured cross sections for the \(^{104,112}\text{Sn} \) pair would have led to a 7% lower \( B(E2) \) assignment for \(^{104}\text{Sn} \). This may be acceptable for many low-statistics experiments, but for future high-accuracy absolute cross-section measurements at energies well above 100 MeV/nucleon we suggest calibration runs of nuclei with known \( B(E2) \) values on a high-Z target and nuclear excitation on a low-Z target. Such an approach allows for the use of very thick reaction targets and thus gives access to more exotic nuclei.

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