Sub-Barrier Coulomb Excitation of ^{106,108,110}Sn

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Abstract. The reduced transition probabilities between the first excited 2^+ state and the 0^+ ground state, $B(E2;0^+ \rightarrow 2^+)$, have been measured in ^{106,108,110}Sn using sub-barrier Coulomb excitation in inverse kinematics at REX-ISOLDE. The results are, $B(E2;0^+ \rightarrow 2^+) = 0.220(22)$, 0.226(17), and 0.228(32) e^2b^2, for ^{110}Sn, ^{108}Sn, and ^{106}Sn, respectively. The results for ^{106,108}Sn are preliminary. De-excitation γ-rays were detected by the MINIBALL Ge-array. The $B(E2)$ reveals detailed information about the nuclear wave function. A shell model prediction based on an effective CD-Bonn interaction in the $\nu(0g_{7/2}, 2s, 1d, 0h_{11/2})$ model space using e^{ν}_{eff} =1.0 e follows the experimental values for the neutron rich Sn isotopes, but fails to reproduce the results presented here.

Keywords: multipole matrix elements, shell model, Coulomb excitation, nuclei with mass number 90 to 149
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INTRODUCTION

The experimental knowledge about the shell structure evolution towards the doubly-magic self-conjugate ^{100}Sn nucleus is now becoming available through radioactive ion beam (RIB) techniques. The investigation of exotic isotopes can reveal novel effects of the underlying effective nucleon-nucleon interaction. Furthermore, the Sn isotopes span a region between the $N = Z = 50$ and $N = 82, Z = 50$ shell closures making it the

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longest isotopic chain available for experiment. This enables a unique study of the shell structure variations as a function of the number of neutrons outside the closed ^{100}Sn core. The constancy of the energy separation between the first excited 2^+ state and the 0^+ ground state in the even-mass Sn isotopes is well explained within the generalized seniority model [1]. Furthermore, according to this theory, non-diagonal matrix elements of the even one-body E2 tensor operator will exhibit a parabolic behaviour as a function of mass number across the Sn isotope chain. Large scale shell-model calculations [2] based on an effective CD-Bonn nucleon-nucleon interaction agree with the generalized seniority model. The adopted experimental $B(E2)$ values on the neutron-rich side of the Sn chain follow the theoretical predictions. The experimental RIB results on ^{106,108,110}Sn presented here and in [2, 3, 4] are consistent with each other and display a clear discrepancy with theoretical models.

EXPERIMENTAL TECHNIQUES

Radioactive ^{110}Sn, ^{108}Sn, and ^{106}Sn beams were produced at ISOLDE by bombarding a thick Lanthanum Carbide primary target by 1 GeV protons. Atomic Sn was ionized through a resonant three-step laser scheme and the isotope of interest was separated using the General Purpose Separator of the facility. The selected isotope was subsequently cooled in a Penning-type trap after which the beam was charge bred in the Electron Beam Ion Source. Post-acceleration was performed by the REX linac. The final beam energy was 2.8 MeV/u, well below the Coulomb barrier in order to exclude any excitation caused by direct nuclear-nuclear overlap. The first 2^+ state was populated through sub-barrier Coulomb excitation against a 2 mg/cm^2 thick ^{58}Ni target. De-excitation γ rays were detected by the highly segmented MINIBALL Ge-array. The recoils and ejectiles were detected by a Double Sided Silicon Strip (DSSSD) detector placed 3 cm from the ^{58}Ni target covering an angular range of about 16°-54°. High segmentation in both γ-ray and particle detectors allowed for a Doppler correction. This is needed since scattered particled had velocities of $\sim 0.05c$. A side effect of using RIBs is the significant γ-ray background caused by unstable nuclei deposited in the target chamber. By gating on prompt particle-γ coincidences the background was reduced. A further gate in the analysis was to select only those events in which both the ejectile and the recoil was detected in the DSSSD, a so called 2p event. Due to the type of inverse kinematics this implied selecting events where both the ejectile and the recoil was scattered with an angle larger than 24°. In the case when only one particle, a so called 1p event, was detected over 24°, due to e.g. noise or double hits, the missing particle could be reconstructed. The integrated Coulomb excitation peaks presented in this paper come from the total set of $1p+2p$ events. The γ-ray statistics was increased by $\sim$10% due to add-back between neighbouring Ge-crystals. It should also be mentioned that the beam did not consist of only the selected Sn isotope, but also of surface ionized In. The contamination originate in the cavity immediately after the primary target. It is of primary importance to map out the isobaric contamination over time. In the case of ^{110}Sn, the beam contamination was not that severe. Due to the high beam intensity of $\sim 10^6$ p/s at the secondary target, the In component could be measured by switching off the laser and register the beam current just before the ^{58}Ni target. The contamination gradually increase as the proton drip line

TABLE 1. Experimental $B(E2)$ values from this work. Note that the values on ^{108,106}Sn are preliminary. The value on ^{110}Sn has previously been published in [3]

Isotope	^{110}Sn	^{108}Sn	^{106}Sn
$B(E2;\uparrow)$ [e^{2}b^2]	0.220(22)	0.226(17)	0.228(32)

is approached. In the ^{106,108}Sn experiments the laser power was recorded continously in the data stream as well as the laser status. The laser was run in on/off mode for one hour every three hours throughout the experiments. In summary, this yielded Sn fractions of $90.0(14)\%$, $58(1)\%$, and $25(1)\%$ for ^{110}Sn, ^{108}Sn, and ^{106}Sn, respectively. It should be pointed out that the intensity of the ^{108}Sn beam was comparable to the ^{110}Sn beam, while for ^{106}Sn it was one order of magnitude lower. This is the primary reason for the larger uncertainty in the $B(E2)$ value for ^{106}Sn. The transition probabilities were extracted by measuring the γ-ray yield coming from the $2^+ \to 0^+$ transition in ^{110,108,106}Sn and normalizing against the corresponding γ-ray yield of the equivalent transition in ^{58}Ni which has a known $B(E2;0^+ \to 2^+)$ value. Angular integration as well as energy loss in the ^{58}Ni target was performed by the coupled-channels code GOSIA2.

RESULTS AND DISCUSSION

The results from this work are presented in Tab. 1 and displayed in Fig. 1. The $B(E2)$

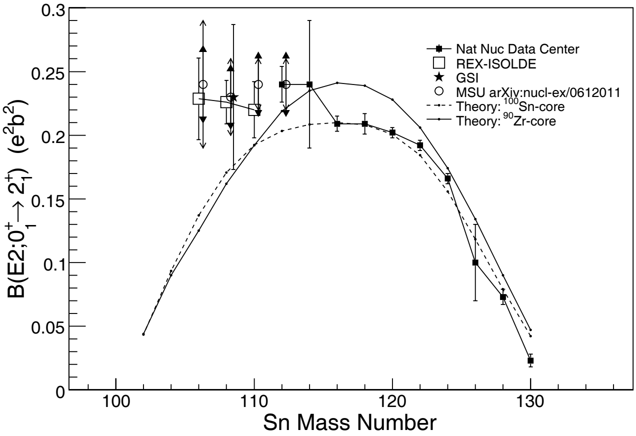

FIGURE 1. The known experimental $B(E2\uparrow)$ values expressed in e^{2}b^2 across the Sn isotope chain. The results from REX-ISOLDE presented in this paper are marked with empty squares. The value on ^{110}Sn has been published in [3]. The value on ^{108}Sn indicated with a star comes from a measurement at GSI [2] using intermediate Coulomb excitation. The empty circles mark the $B(E2)$ values for ^{106,108,110,112}Sn measured at MSU [4] using intermediate Coulomb excitation. The dotted and solid lines extending over the entire isotope chain indicate the result of shell-model calculations [2] using ^{100}Sn (dotted) or ^{90}Zr (solid) as closed shell cores.

values are in disagreement with theoretical predictions based on shell-model calculations using an effective CD-Bonn interaction renormalized with G-matrix theory. The details regarding the calculations presented in Fig. 1 can be found in [2]. It is however worth mentioning that the model space included only $\nu(0g_{7/2}, 2s, 1d, 0h_{11/2})$ with an effective neutron charge $e^{\nu}_{eff} = 1.0$ e. Including proton-neutron excitations from $0g_{9/2}$ was computationally not possible due to the size of the model space. The effect of core-polarization was considered using a seniority truncated model space $\pi(0g1d2s)$ and $\nu(0g_{7/2}1d2s0h_{11/2})$ using $e^{\nu}_{eff} = 0.5$ e and $e^{\pi}_{eff} = 1.5$ e with ^{90}Zr as a closed core. A Relativistic Quasiparticle Random Phase Approximation done in Ref. [5] is consistent with the results presented in this paper but fails to reproduce the adopted $B(E2)$ values in the mid-shell and neutron-rich region. Inclusion of proton-neutron excitations across the $N = Z = 50$ shell gap will of course increase the collectivity of the 2^+ state. This is immediately seen in the ^{90}Zr core calculation in Fig. 1. The observed transition rates reported on here is independent of A indicating that seniority is violated towards ^{100}Sn and implying stronger renormalization effects on the effective charges. The picture is reversed on the neutron rich side of the isotopic chain, where a good shell closure is reached at $N = 82, Z = 50$ as seen in Fig. 1. Furthermore, this region has been studied experimentally to a greater extent. The number of neutrons in the $(0g_{7/2}1d_{5/2})$ plays an important role for the size of the $\pi(0g_{9/2}) - \nu(0g_{7/2}1d_{5/2})$ energy separation. The same effect is responsible for the shell structure evolution between Zr-Sn as the $\pi(0g_{9/2})$ is filled [6, 7]. We are presently preparing a parallel shell-model calculation in an extended model space which includes proton-neutron excitations from the $0g_{9/2}$ orbit.

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