$0^+_{gs} \rightarrow 2^+_1$ Transition Strengths in ^{106}Sn and ^{108}Sn

A. Ekström,[1] J. Cederkäll,[2,1] C. Fahlander,[1] M. Hjorth-Jensen,[3] F. Ames,[4] P. A. Butler,[5] T. Davinson,[6] J. Eberth,[7] F. Fincke,[7] A. Görgen,[8] M. Górska,[9] D. Habs,[10] A. M. Hurst,[5] M. Huyse,[11] O. Ivanov,[11] J. Iwanicki,[12] O. Kester,[9] U. Köster,[2,13] B. A. Marsh,[14,15] J. Mierzejewski,[12,16] P. Reiter,[7] H. Scheit,[17] D. Schwalm,[17] S. Siem,[18] G. Sletten,[19] I. Stefanescu,[11] G. M. Tveten,[2,18] J. Van de Walle,[11] P. Van Duppen,[11] D. Voulot,[15] N. Warr,[7] D. Weisshaar,[7] F. Wenander,[15] and M. Zielińska[8,12]

[1]*Physics Department, University of Lund, Box 118, SE-221 00 Lund, Sweden*
[2]*PH Department, CERN 1211, Geneva 23, Switzerland*
[3]*Physics Department and Center of Mathematics for Applications, University of Oslo, Oslo, Norway*
[4]*TRIUMF, Vancouver, Canada*
[5]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[6]*Department of Physics and Astronomy, University of Edingburgh, Edingurgh, United Kingdom*
[7]*Institute of Nuclear Physics, University of Cologne, Cologne, Germany*
[8]*CEA Saclay, Service de Physique Nucléaire, Gif-sur-Yvette, France*
[9]*Gesellschaft für Schwerionenforschung, Darmstadt, Germany*
[10]*Physics Department, Ludwig-Maximilian University, Munich, Germany*
[11]*Instituut voor Kern- en Stralingsfysica, K. U. Leuven, Leuven, Belgium*
[12]*Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland*
[13]*Institut Laue Langevin, 6 rue Jules Horowitz, 38042 Grenoble, France*
[14]*Department of Physics, University of Manchester, Manchester, United Kingdom*
[15]*AB Department, CERN 1211, Geneva 23, Switzerland*
[16]*Institute of Experimental Physics, University of Warsaw, Warsaw, Poland*
[17]*Max-Planck Institute of Nuclear Physics, Heidelberg, Germany*
[18]*Department of Physics, University of Oslo, Oslo, Norway*
[19]*Physics Department, University of Copenhagen, Copenhagen, Denmark*
(Received 21 February 2008; published 2 July 2008)

The reduced transition probabilities, $B(E2; 0^+_{gs} \rightarrow 2^+_1)$, have been measured in the radioactive isotopes ^{108,106}Sn using subbarrier Coulomb excitation at the REX-ISOLDE facility at CERN. Deexcitation γ rays were detected by the highly segmented MINIBALL Ge-detector array. The results, $B(E2; 0^+_{gs} \rightarrow 2^+_1) = 0.222(19)e^2b^2$ for ^{108}Sn and $B(E2; 0^+_{gs} \rightarrow 2^+_1) = 0.195(39)e^2b^2$ for ^{106}Sn were determined relative to a stable ^{58}Ni target. The resulting $B(E2)$ values are ~30% larger than shell-model predictions and deviate from the generalized seniority model. This experimental result may point towards a weakening of the $N = Z = 50$ shell closure.

DOI: 10.1103/PhysRevLett.101.012502 PACS numbers: 23.20.Js, 21.60.Cs, 25.70.De, 27.60.+j

Precision measurements in unstable nuclei together with recently developed models of the nucleon-nucleon interaction, stemming from many-body techniques and QCD, show promise to improve our understanding of the finer aspects of the dynamics of the atomic nucleus. One approach to this question is to measure reduced transition probabilities—$B(E2; 0^+_{gs} \rightarrow 2^+_1)$—for specific nuclei in the vicinity of a shell closure and to compare these results with calculations based on such models. In particular, one of the pressing questions in nuclear physics today is whether the shell closures, that are well established close to β stability, remain so also for isotopes with a more extreme proton-to-neutron ratio. Intuitive models, such as the generalized seniority scheme [1], predict that these $B(E2)$ values follow a parabolic trend, that peaks at midshell, for a sequence of isotopes between two shell closures. In the following we address the ^{100}Sn shell closure and consequently present results from measurements in the sequence of neutron-deficient even-mass Sn isotopes. This approach has been made possible by newly developed facilities that produce high-quality radioactive ion beams. Recent measurements in ^{110,108}Sn [2–4] consistently deviate from the broken-pair model as given by the generalized seniority scheme and from current large-scale shell-model calculations [2]. Parallel work [4], using intermediate energy Coulomb excitation, suggests a constant trend of the reduced transition probabilities extending to ^{106}Sn. In this Letter we report results from the first measurements of ^{108,106}Sn using subbarrier Coulomb excitation. This is the only experiment so far for ^{106}Sn that has permitted for complete control of the scattering process and thus explicitly fulfills the conditions for safe Coulomb excitation. Our result still deviates significantly from theoretical predictions but indicates a decreasing trend of the $B(E2)$ with a decreasing number of valence particles outside of the ^{100}Sn core. Note that with this Letter three different isotopes have been used for normalization as ^{112}Sn [2] and ^{197}Au [4] have been used previously. All three experiments yield similar

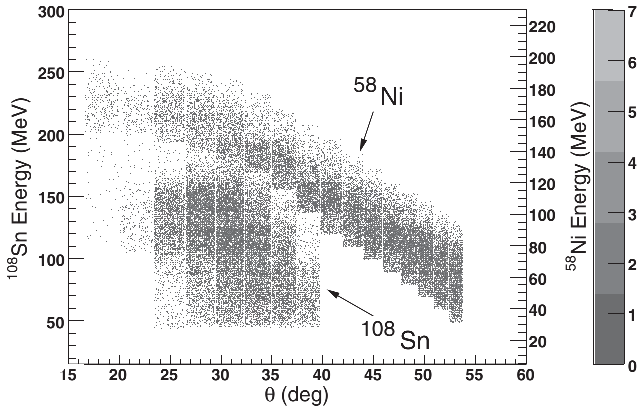

FIG. 1. Energy and angle of the scattered beam and target particles as detected by the DSSSD. The kinematic cuts used to distinguish between ejectiles and recoils have been applied to the data. The corresponding plot for the ^{106}Sn case is similar.

results for ^{110,108}Sn. Thus, it appears that the difference between theory and observation is of physical origin. Our result for ^{106}Sn now clearly shows that the seniority model describes the structural evolution of the neutron-rich Sn isotopes well, but for the light Sn isotopes this interpretation appears to break down.

The experiment was carried out at the REX-ISOLDE [5] facility at CERN. The radioactive beams were produced by bombarding a 27 g/cm^2 LaC$_x$ primary target by 1.4 GeV protons delivered by the CERN PS Booster. Atomic Sn was singly ionized using a resonant three-step laser scheme and extracted by an electric potential. Beams with mass numbers $A = 108$ or $A = 106$ were selected by electromagnetic separation. The half-lives of ^{108}Sn and ^{106}Sn are 10.30(8) min and 115(5) s [6], respectively. The beam was charge bred for 67 ms in an electron beam ion source [7] in order to reach the 26$^+$ charge state used for post-acceleration. The final energy was 2.82 and 2.83 MeV/u for the $A = 108$ and $A = 106$ beams, respectively. This is well below the safe bombarding energy [8] of ~3.6 MeV/u, corresponding to a 5 fm separation of the nuclear surfaces. The 2 mg/cm^2 ^{58}Ni target was isotopically enriched to 99.9%. The first excited 2$^+$ state in ^{58}Ni, used for normalization, is located at 1454 keV, and has an adopted $B(E2; 0^+_{gs} \rightarrow 2^+_1) = 0.0705(18)e^2b^2$ [6]. Emitted γ rays were registered in the MINIBALL [9] detector array which surrounds the target in a close to 4π configuration. Energy and scattering angle of ejectiles and recoils were detected by a circular double sided silicon strip detector (DSSSD) [10] placed 30 mm downstream from the target (see Fig. 1). Data were recorded using two trigger conditions. The first one was generated by particle-γ coincidence events with a time window of 800 ns and the second one by events arising from one or more particles detected in the DSSSD. The latter trigger was downscaled by a factor of 2^6. Ejectiles and recoils were easily separated offline due to the kinematics. In brief, the results presented in this Letter were obtained with the following conditions on the data: (a) coincident particle-γ events; (b) kinematic separation of ejectiles and recoils; (c) selection of two-particle (2p) events and kinematic reconstruction using one-particle (1p) events.

Figure 2 shows the Coulomb excitation γ-ray peaks after imposing the analysis conditions and correcting for Doppler broadening. The lasers were switched on and off with 14.4 s intervals for 1 h every 3 h throughout the experiments in order to measure the composition of the scattered beam over time. Using this information, in combination with the constant cross section for the Coulomb excitation of the contaminants, the respective Sn fractions could be determined over the full duration of the experiments and were 59.0(27)% and 29.2(42)% for the ^{108}Sn and ^{106}Sn beams, respectively. Further details will be published in a forthcoming paper [11]. The $B(E2)$ values were extracted from the experimental data using the coupled-channels Coulomb excitation code GOSIA2 [12]. Note that the static quadrupole moment $Q(2^+_1)$ in ^{112}Sn is consistently $0b$ [13]. For this reason a $Q(2^+_1) = 0b$ was used also in the current analysis. Input parameters and results are displayed in Table I and in Figs. 2 and 3. As can be seen in Fig. 3 the results deviate from the theoretical prediction by

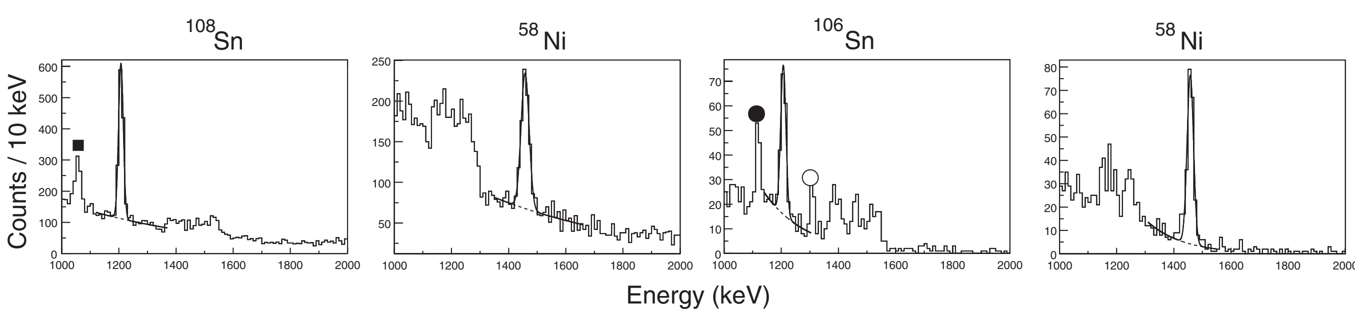

FIG. 2. 2p + 1p Doppler corrected γ-ray spectra from the ^{108}Sn and ^{106}Sn experiments. The peak indicated by ■ comes from two closely located ^{108}In decay γ rays that merge due to Doppler correction. The γ ray marked with ● is the deexcitation from the 8$^+$ state at 1118 keV to the 7$^+$ ground state in ^{106}In [24]. Similarly the γ ray marked with ○ is the deexcitation from the 9$^+$ state at 1307 keV to the ground state in the same nucleus.

TABLE I. The two rightmost columns give background information as well as results for the two cases discussed in the text. The last row gives the $B(E2)$ values.

Data	$A = 108$[a]	$A = 106$[b]
$E(2^+)$ (keV)	1206	1206
γ-ray yield (Ni)	577 (34)	207(15)
γ-ray yield (Sn)	994(38)	133(14)
FWHM (Sn) (keV)	19.3(8)	22.5(26)
FWHM (Ni) (keV)	33.1(18)	26.5(24)
$B(E2;\uparrow)$ (e^2b^2)	0.222(19)	0.195(39)

[a]2.82 MeV/u ^{108}Sn on 2.0 mg/cm^2 ^{58}Ni.
[b]2.83 MeV/u ^{106}Sn on 2.0 mg/cm^2 ^{58}Ni.

more than 1σ. According to the seniority model the $B(E2)$ values naturally decrease with a decreasing number of particles outside the closed core. This trend can be noted in our data for ^{106}Sn. The precision of our result can be put in perspective in the following way. The relative uncertainty for our ^{108}Sn and ^{106}Sn measurements are 9% and 20%, respectively. The uncertainty for the ^{108}Sn measurement reported in Ref. [2] was 25% whereas the corresponding total uncertainty for the ^{108}Sn and ^{106}Sn measurements in Ref. [4] was 17% and 24%. We again note that the present experiment for ^{106}Sn is currently the only one to explicitly fulfill the safe condition. As stated in Ref. [4], the reported $B(E2; 0_{\mathrm{gs}} \rightarrow 2_1^+) = 0.240 \pm 0.050 \pm 0.030 e^2b^2$ value for ^{106}Sn in that study was extracted with a relaxed constraint on the impact parameter. Interestingly, our value for ^{106}Sn measured with safe Coulomb excitation does not render a constant trend.

The relative purity of the low-energy excited states in the even-mass Sn isotopes makes them suitable for a shell-model analysis. The relevant model space for neutrons and protons outside of the ^{100}Sn core consists of the $1d_{5/2}0g_{7/2}2s_{1/2}1d_{3/2}0h_{11/2}$ orbits. The first orbit below the $N = Z = 50$ shell gap is $0g_{9/2}$. It is natural to assume that the missing $0_{\mathrm{gs}}^+ \rightarrow 2_1^+$ transition strength, for the ^{100}Sn core calculation (see Fig. 3), can partly be accounted for by proton core excitations. Similarly, neutron excitations across the shell gap would also increase the $E2$ strength. These excitations would be enhanced by a strong $E2$ coupling between the $0g_{9/2}$ and $1d_{5/2}$ orbits. Since the $0g_{7/2}1d_{5/2}$ orbits start to dominate the configurations with a decreasing number of neutrons outside the core the available phase space for excitations of this kind increases. However, as the experimental $B(E2; 0_{\mathrm{gs}}^+ \rightarrow 2_1^+)$ increases already when going from ^{116}Sn to ^{114}Sn, it appears that proton excitations play an important role in the transition. A shell-model calculation based on an extended model space that includes a limited number of $0g_{9/2}$ protons and neutrons is on the verge of computational feasibility. A coupling to orbits outside of the model space is approximately accounted for in many-body theory by the perturbative construction of the effective interaction [14]. Previous calculations based on a ^{100}Sn core indicated the need for an explicitly expanded model space. Banu *et al.* [2] included this effect up to 4p-4h proton core excitations by means of a seniority truncated model space outside of a ^{90}Zr core. Because of the seniority truncation in that calculation the symmetric trend of the $B(E2)$ values was retained. The impact of core excitations on the $0_{\mathrm{gs}}^+ \rightarrow 2_1^+$ transition probability depends in part on the $0g_{9/2} - 1d_{5/2}$ energy separation, E_g. In a limited $0g_{9/2}0g_{7/2}1d_{5/2}$ neutron model space a $\sim$50% increase of the $B(E2)$ can be noted with a $\sim$50% reduction of E_g from 6 to 3 MeV. Neither the proton nor the neutron $0g_{9/2}^{-1}1d_{5/2}$ coupling strength is known from experiment. The so-called monopole drift of the single-particle orbits can play a key role in self-conjugate nuclei.

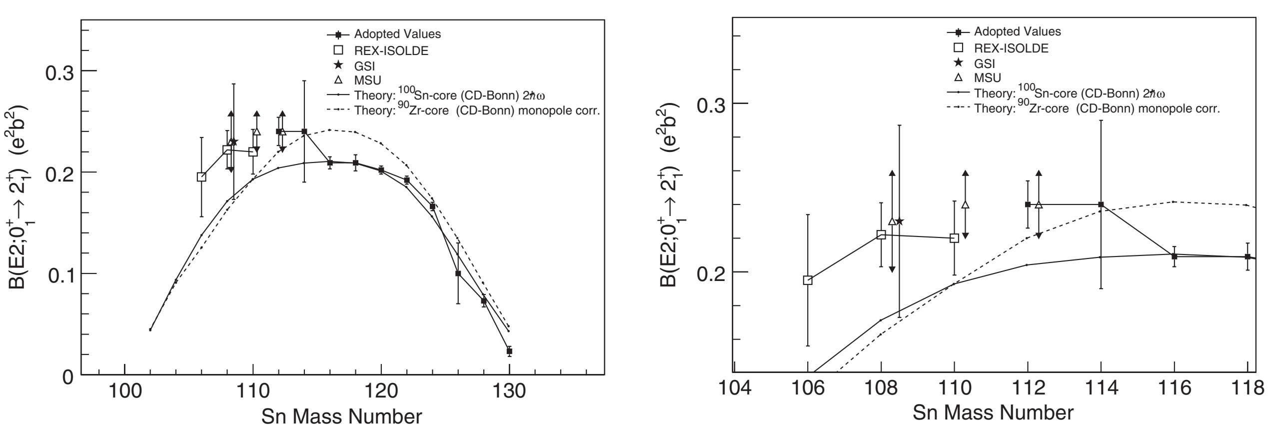

FIG. 3. Left panel: Experimental and theoretical $B(E2)$ values. The dashed curve represents the result from a shell-model calculation using ^{100}Sn as core and a $\nu(g_{7/2}, d, s, h_{11/2})$ model space with a neutron effective charge $e_{\mathrm{eff}}^{\nu} = 1.0e$. The solid line corresponds to using ^{90}Zr as core and a $\pi(g, d, s) - \nu(g_{7/2}, d, s, h_{11/2})$ model space with $e_{\mathrm{eff}}^{\nu} = 0.5e$. Right panel: Enlarged version of the left panel. Only experimental results fulfilling the safe condition are shown in the two panels.

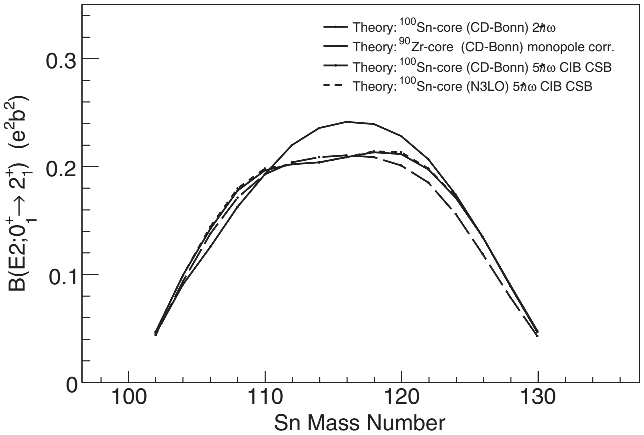

FIG. 4. Theoretical $B(E2)$ values given in e^2b^2 for the even-mass Sn isotopes. The first two calculations are identical to Fig. 3. The ^{90}Zr core calculation was seniority truncated and based on a monopole corrected CD-Bonn interaction [2]. The remaining calculations are based either on the N3LO interaction or a more recent CD-Bonn interaction. The number of excitations allowed in the perturbative scheme is here $5\hbar\omega$. Whether the interaction incorporated charge symmetry breaking (CSB) and charge independence breaking (CIB) is indicated in the legend.

It was shown in Ref. [15] that the interaction between neutrons and protons in $j = \ell \pm 1/2$ orbits modifies the effective single-particle energies, as observed for instance in Ref. [16]. With this line of reasoning, the neutron-deficient Sn isotopes could exhibit a tendency for the proton $0g_{9/2}$ to become less bound as the number of neutrons in $0g_{7/2}$ decreases. This type of single-particle drift was also observed in the Zr isotopes [17]. Further experimental evidence for monopole drift along isotone chains come from (d, p) and (d, t) reactions [18]. Analysis of isomeric core excited states in ^{98}Cd gives a ^{100}Sn shell gap of ~6.5 MeV for both neutrons and protons [19]. Also, the energy of the $25/2^+$ level, with a dominating $\nu 0g_{9/2}^{-1}$ component, in ^{99}Cd points towards a shell gap of the same size [20]. However, recent experimental results for the three first excited states in the $N = Z + 2$ nucleus ^{110}Xe instead point towards a possible weakening of the $N = Z = 50$ shell closure [21]. For this Letter we have expanded the shell-model calculations in Ref. [2] by using two more recent nucleon-nucleon interactions (see Fig. 4). One, which is based on chiral effective field theory, N3LO [22], includes pions and nucleons as the only effective degrees of freedom. The other one is a more recent type of charge-dependent (CD)-Bonn interaction [23]. In contrast to the calculations in Ref. [2], we have added here the Coulomb interaction as well and explicitly break the charge symmetry and charge independence between the nucleons. The divergent two-body matrix elements were renormalized using G-matrix theory and tailored to the model space using many-body perturbation techniques [14]. Interaction terms of two-body matrix elements up to third order were included in this treatment and the maximum energy of intermediate excitations was increased to a limit of $5\hbar\omega$. As can be seen in Fig. 4 the trend of the $B(E2)$ values is sensitive to the coupling to orbits outside of the model space. With these new microscopic interactions the calculations show a deviation from the symmetry expected in the seniority model. Further progress involves using these interactions in an explicitly expanded model space which relies on parallelized calculations carried out on a computational cluster. Work towards this end has recently been initiated.

In this Letter we have reported on Coulomb excitation experiments using ^{108,106}Sn beams at REX-ISOLDE. With this the $B(E2)$ systematics from safe Coulomb excitation now extend down to ^{106}Sn. Calculations using the N3LO nucleon-nucleon interaction and a recent CD-Bonn interaction show an interesting deviation from the symmetric trend predicted by the seniority model but still do not reproduce the experimental data. This observed increase in transition strength clearly shows the need for further theoretical investigations of the nucleon-nucleon interaction as applied to the ^{100}Sn shell closure.

This work was supported by the European Union through RII3-EURONS (Contract No. 506065) and the German BMBF through Grant No. 06 KY 205 I.

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