2\sp1\sp+ → 0\sp1\sp+ transition strengths in Sn nuclei


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(Received 10 May 2007; published 20 August 2007)

The lifetime of the 2\sp1\sp+ state at 1256.7 keV in \textsuperscript{112}Sn has been determined using the (n,n'γ) reaction. Angular distribution measurements were carried out at a neutron energy of 1.7 MeV, above the 2\sp1\sp+ energy threshold and below that of the second excited level. Through the Doppler-shift attenuation method, the lifetime of the 2\sp1\sp+ state is determined as 750\sp±50 fs, which gives a B(E2; 2\sp1\sp+ → 0\sp1\sp+) value of 10.9\sp±1.5 W.u. This E2 strength in \textsuperscript{112}Sn also allows a redermination of the B(E2; 2\sp1\sp+ → 0\sp1\sp+) in \textsuperscript{108}Sn as 10.8(3.0) W.u. These values result in a symmetric trend around the neutron midshell in the systematics of E2 strengths in the even-mass tin isotopes and do not support N = 64 or N = 66 subshell gaps. The symmetric trend is in agreement with recent shell model predictions, where proton-core excitations were allowed in the calculations.

DOI: 10.1103/PhysRevC.76.021302

PACS number(s): 21.10.Re, 21.10.Tg, 21.60.Cs, 23.20.–g

With a large number of stable isotopes and the Z = 50 shell closure, the tin nuclei provide an ideal testing ground for systematic studies of both individual-particle and collective nature. From the increased excitation energies of the 2\sp1\sp+ states in \textsuperscript{114}Sn and \textsuperscript{116}Sn as compared with other Sn isotopes (see Fig. 1), Pauling concluded that either the former involve the wave functions of the initial and final states. From the experimental B(E2; 2\sp1\sp+ → 0\sp1\sp+) values in the even-mass Sn isotopes (shown in Fig. 2 with data taken from Refs. [2,3]), evidence for subshell gaps. The symmetric trend is in agreement with recent shell model predictions, where proton-core excitations were proposed [3]. Large-scale shell-model calculations were performed using a new effective interaction obtained from the CD-Bonn nucleon-nucleon potential [9] and the G–matrix prescription [10]. Predictions using \textsuperscript{100}Sn and \textsuperscript{90}Zr as closed-shell cores poorly reproduced the experimental B(E2; 2\sp1\sp+ → 0\sp1\sp+) values if only neutron valence excitations were considered [3]. Despite the ambiguity of experimental single-particle energies of odd-mass Sn isotopes and, hence, uncertainty of the monopole strength in the effective interaction, some agreement was reached when both proton- and neutron-core excitations were included in an untruncated gds shell-model space [3]. Nevertheless, the experimental B(E2; 2\sp1\sp+ → 0\sp1\sp+) values in \textsuperscript{108}Sn and \textsuperscript{112}Sn clearly exceed predictions, even when a maximum number of four proton particle-hole excitations were allowed in the calculations. Further encouraging relativistic mean-field calculations by Ansari and Ring [11] predict the enhancement of B(E2) values in the Sn isotopes with the decrease of mass number, A, with a maximum around A = 106. Such an enhancement is related to the increasing contribution of protons to the total wave function normalization. Here, the authors claim the need for a new fix of the force parameters used in the calculations since different sets of force parameters give quite different results.

Although the B(E2; 2\sp1\sp+ → 0\sp1\sp+) value in \textsuperscript{112}Sn seems accurately determined, the lifetime of the 2\sp1\sp+ state has not been directly measured through Doppler-shift methods. In addition, the asymmetric trend in the systematics of E2 strengths in the even-mass tin isotopes, as well as the disagreement with shell-model predictions, demands a further examination of the B(E2; 2\sp1\sp+ → 0\sp1\sp+) value in \textsuperscript{112}Sn by other experimental probes. Recently, \textsuperscript{112}Sn has been studied through the (n,n’γ) reaction by Kumar and collaborators [12]; however, the high neutron energies (2.9 and 3.8 MeV) used in the angular-distribution measurements lead to feeding from higher-lying levels and hinder a direct lifetime determination of the 2\sp1\sp+ state at 1256.7 keV. In this work, we present a similar angular-distribution study of \textsuperscript{112}Sn, but at a lower neutron energy. The lifetime of the 2\sp1\sp+ state, determined with the Doppler-shift attenuation method, yields a new value for the 2\sp1\sp+ → 0\sp1\sp+ transition strength, which is used to examine the trend of B(E2; 2\sp1\sp+ → 0\sp1\sp+) values in the even-mass tin isotopes.

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0556-2813/2007/76(2)/021302(4) 021302-1 ©2007 The American Physical Society
The first excited state of $^{112}$Sn was populated through the inelastic neutron scattering reaction. A 3.91-g metallic sample enriched to 99.5% in $^{112}$Sn was bombarded with nearly monoenergetic neutrons ($\Delta E \approx 60$ keV). Pulsed proton beams with a 1.875-MHz repetition rate and with a pulse width of $\sim 1$ ns were obtained from the electrostatic accelerator at the University of Kentucky, and neutrons were produced by the $^3$H(p,n)$^3$He reaction. The $\gamma$ rays from the $(n,n'\gamma)$ reaction were observed using a BGO Compton-suppressed high-purity germanium (HPGe) detector with a relative efficiency of 55% and an energy resolution of 1.8 keV (FWHM) at 1332 keV. The detector was located 1.19 m from the scattering sample, and time-of-flight techniques were used for prompt $\gamma$-ray gating to suppress background radiation and improve the quality of the data.

Angular distribution measurements were carried out at a neutron energy of 1.7 MeV and at 10 different angles ranging from 40$^\circ$ to 150$^\circ$. The 1.7-MeV neutron energy was chosen to populate the $2^+_1$ state at 1256.7 keV yet to avoid feeding from higher-lying levels. The energy spectrum was monitored with a $^{60}$Co radioactive source, which decays to $^{60}$Ni with the emission of 1173.237 and 1332.501 keV $\gamma$ rays and served as an energy reference. A detailed description of the experimental setup may be found elsewhere [13,14]. In addition, similar angular distribution measurements were performed at 1.7 MeV using the same $^{112}$Sn sample integrated with natural tin for comparison with well-known lifetimes in $^{116}$Sn and $^{118}$Sn. The composite sample was a 12.43-g cylinder (3.91 g from $^{112}$Sn and 8.52 g from natural tin) with a height of 2.0 cm and a diameter of 1.2 cm. Figure 3 shows energy spectra at 40$^\circ$ from the two angular-distribution measurements performed in this work.

Lifetimes were determined through the Doppler-shift attenuation method following the $(n,n'\gamma)$ reaction [15]. Here, the shifted $\gamma$-ray energy is given by

$$E_{\gamma'}(\theta_{\gamma'}) = E_{\gamma} + \frac{v_0}{c} F(\tau) \cos \theta_{\gamma'},$$  \hspace{1cm} (1)

with $E_{\gamma}$ being the unshifted $\gamma$-ray energy, $v_0$ the initial recoil velocity in the center of mass frame, $\theta$ the angle of observation, and $F(\tau)$ the attenuation factor, which is related to electronic and nuclear stopping processes described by Blaugrund [16]. Finally, the lifetimes of the states can be determined by comparison with the $F(\tau)$ values calculated using the Winterbon formalism [17].

For comparison purposes, we have redetermined the lifetimes of the $2^+_1$ states in $^{116}$Sn and $^{118}$Sn as 730$^{+295}_{-206}$ and 850$^{+250}_{-180}$ fs, respectively. The lifetime of the $2^+_1$ state in $^{116}$Sn is in general agreement with nuclear resonance scattering [18–21] and Coulomb-excitation [22] measurements. However, from indium contained in our HPGe spectrometer, the 1293.6-keV transition de-exciting the $2^+_1$ level in $^{116}$Sn has an $\sim 8\%$ $^{115}$In$(n,\gamma')$ component that has no Doppler shift. Allowance for that uncertainty has been included. The current lifetime measurement in $^{118}$Sn, shown in Fig. 4, is also in general agreement with Coulomb-excitation [23] and $(\gamma,\gamma')$ [20,24] measurements, which led to lifetimes of 700(30) and 665(45) fs, respectively.

The fits to the Doppler-shift attenuation data for the 1256.7-keV $\gamma$-ray de-exciting the $2^+_1$ state in $^{112}$Sn are plotted in Fig. 5 and give lifetimes of $\tau = 745^{+170}_{-120}$ and $\tau = 760^{+175}_{-130}$ fs,
in measurements taken with the $^{112}\text{Sn}$ sample only and $^{112}\text{Sn}$ together with natural tin, respectively. The weighted average gives $\tau = 750^{+125}_{-90}$ fs and an $E2$ strength to the ground state of $10.9^{+1.5}_{-1.6}$ W.u. This $B(E2; 2^+_1 \rightarrow 0^+_1)$ value is in disagreement with the value of $15.2(9)$ W.u. given in the Nuclear Data Sheets [25]. In particular, this disagreement arises because shorter lifetimes were determined in Coulomb-excitation studies [5,6], whereas the lifetime of $707(160)$ fs determined through $(\alpha, \alpha')$ inelastic scattering measurements is in good agreement with our data [7]. As the $B(E2; 2^+_1 \rightarrow 0^+_1)$ value of $15.1(3.7)$ W.u. in $^{108}\text{Sn}$ was obtained by normalizing to the former $B(E2; 2^+_1 \rightarrow 0^+_1)$ value in $^{112}\text{Sn}$ [3], we can also re-determine the $E2$ strength in $^{108}\text{Sn}$ using the same prescription given by Banu and co-workers [3]. The result is a smaller $B(E2; 2^+_1 \rightarrow 0^+_1)$ value of $10.8(3.0)$ W.u. The revised $B(E2; 2^+_1 \rightarrow 0^+_1)$ values determined in this work for $^{108}\text{Sn}$ and $^{112}\text{Sn}$ are plotted as circles in Fig. 6.

When we include our new data in Fig. 2, and despite the large uncertainty of the $B(E2; 2^+_1 \rightarrow 0^+_1)$ value in $^{114}\text{Sn}$, a characteristic symmetric trend emerges in the systematics of the $E2$ strengths around midshell $N = 66$. In a recent Coulomb excitation measurement of $^{110}\text{Sn}$ [26], a $B(E2; 2^+_1 \rightarrow 0^+_1)$ value of $14.05(1.41)$ W.u. has been determined, in agreement with the enhancement of $B(E2)$ values proposed by Banu and co-workers [4] (as shown in Figs. 2 and 6), and in disagreement with the parabolic trend predicted by shell model calculations. The value obtained for $^{110}\text{Sn}$ was normalized to the previously accepted $B(E2; 2^+_1 \rightarrow 0^+_1)$ in $^{58}\text{Ni}$ of 10.42(30) W.u. (or $B(E2; 0^+_1 \rightarrow 2^+_1) = 0.0695(20) e^2 b^2$ [26]). A recent update of the nuclear data base (ENSDF) in September 2006 establishes a strikingly different $B(E2; 2^+_1 \rightarrow 0^+_1)$ value of 7.4(1) W.u., in agreement with the only direct lifetime measurement of the $2^+_1$ state in $^{58}\text{Ni}$ [27]. This decrease in the collectivity of the $2^+_1$ state in $^{58}\text{Ni}$ would lead to a similar shift in the data point for $^{110}\text{Sn}$. When compared with previous shell-model calculations [3], the reduction in $B(E2; 2^+_1 \rightarrow 0^+_1)$ values in $^{108}\text{Sn}$ and $^{112}\text{Sn}$ implies that even while proton-core polarization effects are still important contributions to the $E2$ strengths, the inclusion of four proton particle-hole excitations in the untruncated gds shell-model space seems excessive. Just two-proton (particle-hole) core excitations or even four proton (particle-hole) excitations truncated to the $0g_{9/2}, 2g_{7/2}, 1d_{5/2}$ orbitals seems to reproduce the data well, given the strong assumptions of an $N = 50$ shell closure and the ambiguity of the monopole strengths of single-particle states. Finally, although our results do not support the existence of an $N = 64$ subshell, the large uncertainty of the $B(E2; 2^+_1 \rightarrow 0^+_1)$ value in $^{114}\text{Sn}$ clearly needs to be addressed in future experiments.

In conclusion, we have determined a lifetime of $\tau = 750^{+125}_{-90}$ fs for the $2^+_1$ state in $^{112}\text{Sn}$. This lifetime is somewhat longer than that determined in previous measurements and gives a $B(E2; 2^+_1 \rightarrow 0^+_1)$ value of $10.9^{+1.5}_{-1.6}$ W.u. By renormalizing to this value, we obtain a $2^+_1 \rightarrow 0^+_1 E2$ strength of $10.8(3.0)$ W.u. in $^{108}\text{Sn}$. When compared with the systematics of $E2$ strengths in the even-mass Sn isotopes, a symmetric trend emerges around $N = 66$, in agreement with recent shell-model calculations where proton-core excitations were allowed. This lower collectivity in the light Sn isotopes does

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**FIG. 4.** (Color online) Doppler-shift attenuation data for the $\gamma$-ray transition de-exciting the $2^+_1$ state at 1229.7 keV in $^{118}\text{Sn}$. Phys. Rev. C 76, 021302(R) (2007)

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**FIG. 5.** (Color online) Doppler-shift attenuation data for the $\gamma$-ray de-exciting the $2^+_1$ state at 1256.7 keV in $^{112}\text{Sn}$ from angular distribution measurements using $^{112}\text{Sn}$ only (top panel) and $^{112}\text{Sn}$ with natural tin (bottom panel). The weighted average gives $\tau = 750^{+125}_{-90}$ fs.

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**FIG. 6.** (Color online) $B(E2; 2^+_1 \rightarrow 0^+_1)$ values in even-mass Sn isotopes. Data from Refs. [2–4] are shown as diamonds, and the new $B(E2; 2^+_1 \rightarrow 0^+_1)$ values for $^{108}\text{Sn}$ and $^{112}\text{Sn}$ are given in open circles.
not necessarily support \( N = 64 \) or \( N = 66 \) as semimagic closed shells. Moreover, an untruncated \( gds \) major shell-model space is not needed to explain the lower \( B(E2; 2^+_1 \rightarrow 0^+_1) \) values determined in this work.

In the near future, we plan to study \(^{114}\text{Sn}\) through the \((n,n'\gamma)\) reaction, where we expect to determine the lifetime of the \( 2^+_1 \) state and the \( 2^+_1 \rightarrow 0^+_1 \) transition strength. If successful, this result will shed light on core-polarization effects from the \( Z = 50 \) shell closure as well as on the possibility of an \( N = 64 \) semimagic closed shell.

The authors gratefully acknowledge fruitful discussions with F. Nowacki and the assistance of H. E. Baber. We thank J. A. Becker, E. B. Norman, and L. A. Bernstein for their assistance with the isotopically enriched material used in these measurements. This work was partially supported by the U.S. National Science Foundation under Grant No. PHY-0354656.

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