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$2_1^+ \rightarrow 0_1^+$ transition strengths in Sn nuclei

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The lifetime of the 2_1^+ state at 1256.7 keV in ^{112}Sn has been determined using the $(n,n'\gamma)$ reaction. Angular distribution measurements were carried out at a neutron energy of 1.7 MeV, above the 2_1^+ energy threshold and below that of the second excited level. Through the Doppler-shift attenuation method, the lifetime of the 2_1^+ state is determined as 750^{+125}_{-90} fs, which gives a $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of $10.9^{+1.5}_{-1.6}$ W.u. This $E2$ strength in ^{112}Sn also allows a redetermination of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ in ^{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.

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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_1^+ states in ^{114}Sn and ^{116}Sn as compared with other Sn isotopes (see Fig. 1), Pauling concluded that either $N = 64$ or $N = 66$ could be considered semimagic [1]. Reduced transition probabilities test nuclear structure in still greater detail than excitation energies, because the former involve the wave functions of the initial and final states. From the experimental $B(E2; 2_1^+ \rightarrow 0_1^+)$ values in the even-mass Sn isotopes (shown in Fig. 2 with data taken from Refs. [2,3]), evidence for subshell effects is not obvious. The light tin isotopes, up to $N = 64$, present an asymmetry in $E2$ strengths with respect to the heavier isotopes. The ambiguous trend in the light tin isotopes could be attributed partially to the large uncertainties of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ values in ^{108}Sn and ^{114}Sn, and the recently determined $E2$ strength in ^{110}Sn [4]. In ^{112}Sn, nonetheless, a $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of 15.2(9) W.u., with only a 6% uncertainty, clearly deviates from the trend observed in the heavier Sn isotopes. The $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of 15.1(3.7) W.u. in ^{108}Sn [3] has recently been obtained from intermediate-energy Coulomb excitation in inverse kinematics by normalizing to the accepted $B(E2; 2_1^+ \rightarrow 0_1^+)$ of 15.2(9) W.u. in ^{112}Sn. The latter strength was obtained from previous Coulomb-excitation [5,6] and (α, α') inelastic scattering [7] measurements, which yield an accepted lifetime of $\tau = 535(30)$ fs for the 2_1^+ state [8].

In the Coulomb-excitation study of ^{108}Sn by Banu and collaborators [3], unexpected shell effects have been suggested in the even-mass Sn isotopes. The $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of 15.1(3.7) W.u. in ^{108}Sn was compared with experimental data and shell-model predictions in the other even-mass Sn isotopes. Consequently, the break-up of the $Z = 50$ closed shell and the presence of strong 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 ^{100}Sn and ^{90}Zr as closed-shell cores poorly reproduced the experimental $B(E2; 2_1^+ \rightarrow 0_1^+)$ values if only neutron valence excitations were considered [3]. Despite the ambiguity of experimental single-particle energies from 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 $B(E2; 2_1^+ \rightarrow 0_1^+)$ values in ^{108}Sn and ^{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 $B(E2; 2_1^+ \rightarrow 0_1^+)$ value in ^{112}Sn seems accurately determined, the lifetime of the 2_1^+ 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 $B(E2; 2_1^+ \rightarrow 0_1^+)$ value in ^{112}Sn by other experimental probes. Recently, ^{112}Sn has been studied through the $(n,n'\gamma)$ 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_1^+ state at 1256.7 keV. In this work, we present a similar angular-distribution study of ^{112}Sn, but at a lower neutron energy. The lifetime of the 2_1^+ state, determined with the Doppler-shift attenuation method, yields a new value for the $2_1^+ \rightarrow 0_1^+$ transition strength, which is used to examine the trend of $B(E2; 2_1^+ \rightarrow 0_1^+)$ values in the even-mass tin isotopes.

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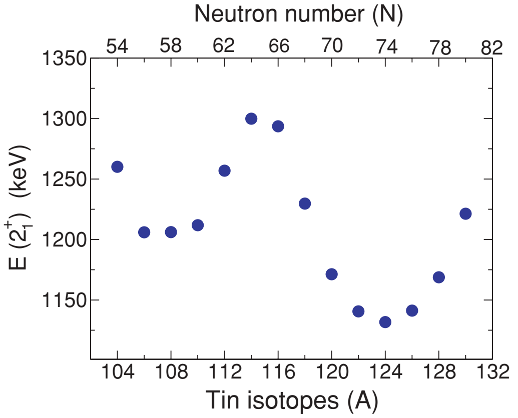

FIG. 1. (Color online) Excitation energies of the 2_1^+ states in even-mass Sn isotopes.

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 ($\Delta E \sim 60$ keV). Pulsed proton beams with a 1.875-MHz repetition rate and with a pulse width of ~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 γ 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 γ-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° to 150°. 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 γ 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° from the two angular-distribution measurements performed in this work.

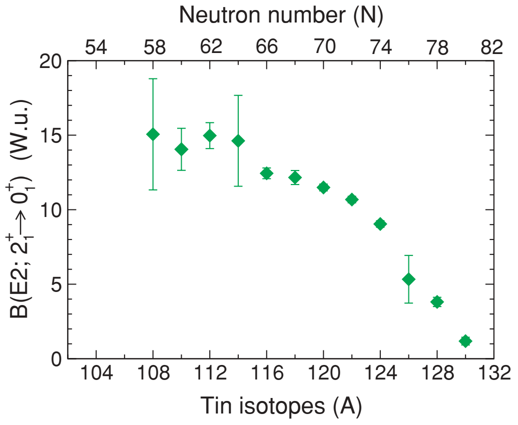

FIG. 2. (Color online) $B(E2; 2_1^+ \rightarrow 0_1^+)$ values in even-mass tin isotopes. Data are taken from previous work [2–4].

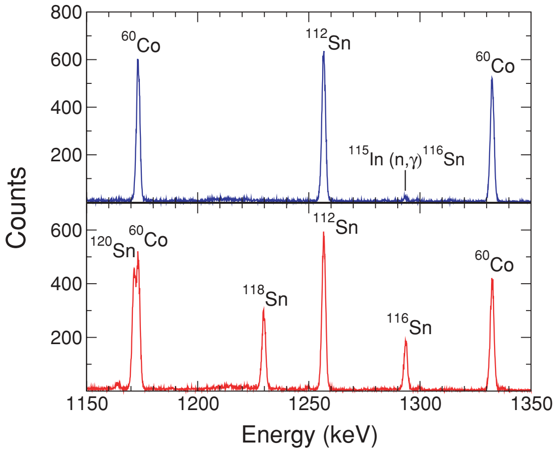

FIG. 3. (Color online) γ-ray spectra from the ^{112}Sn$(n,n'\gamma)$ reaction obtained at 40° with an incident neutron energy of 1.7 MeV for the ^{112}Sn sample (top panel) and the composite sample (^{112}Sn and natural tin; bottom panel).

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

$$E_\gamma(\theta_\gamma) = E_{\gamma_0}\left[1 + \frac{v_0}{c}F(\tau)\cos\theta_\gamma\right], \qquad (1)$$

with E_{γ_0} being the unshifted γ-ray energy, v_0 the initial recoil velocity in the center of mass frame, θ 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}_{-200} 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 ~8% ^{115}In(n,γ) 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 (γ,γ') [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 γ-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,

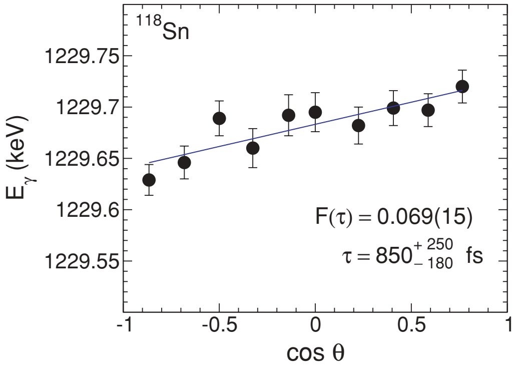

FIG. 4. (Color online) Doppler-shift attenuation data for the γ-ray transition de-exciting the 2_1^+ state at 1229.7 keV in ^{118}Sn.

in measurements taken with the ^{112}Sn sample only and ^{112}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 (α, α') 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}Sn was obtained by normalizing to the former $B(E2; 2_1^+ \rightarrow 0_1^+)$ value in ^{112}Sn [3], we can also redetermine the $E2$ strength in ^{108}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}Sn and ^{112}Sn are plotted as circles in Fig. 6.

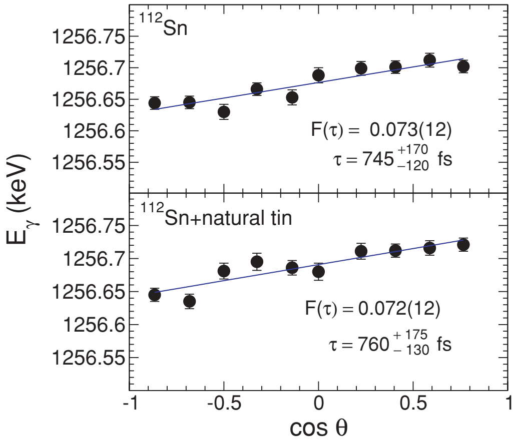

FIG. 5. (Color online) Doppler-shift attenuation data for the γ-ray de-exciting the 2_1^+ state at 1256.7 keV in ^{112}Sn from angular distribution measurements using ^{112}Sn only (top panel) and ^{112}Sn with natural tin (bottom panel). The weighted average gives $\tau = 750^{+125}_{-90}$ fs.

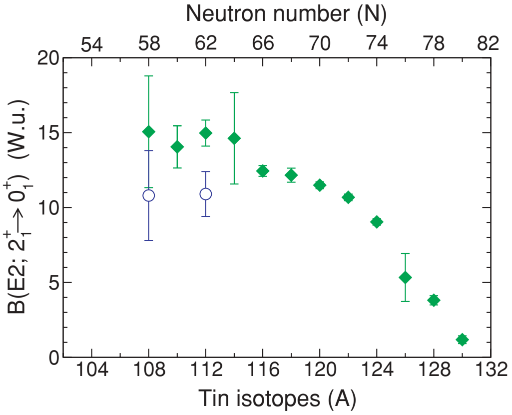

FIG. 6. (Color online) $B(E2; 2_1^+ \rightarrow 0_1^+)$ values in even-mass tin isotopes. Data from Refs. [2–4] are shown as diamonds, and the new $B(E2; 2_1^+ \rightarrow 0_1^+)$ values for ^{108}Sn and ^{112}Sn are given in open circles.

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}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}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}Sn was normalized to the previously accepted $B(E2; 2_1^+ \rightarrow 0_1^+)$ in ^{58}Ni of 10.42(30) W.u. (or $B(E2; 0_1^+ \rightarrow 2_1^+) = 0.0695(20)\, e^2b^2$ [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}Ni [27]. This decrease in the collectivity of the 2_1^+ state in ^{58}Ni would lead to a similar shift in the data point for ^{110}Sn. When compared with previous shell-model calculations [3], the reduction in $B(E2; 2_1^+ \rightarrow 0_1^+)$ values in ^{108}Sn and ^{112}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 $0g_{9/2}$, $0g_{7/2}$, $1d_{5/2}$ 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}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}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}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 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}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.

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