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Lifetime measurements and low-lying structure in ^{112}Sn

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Abstract. The low-lying structure of ^{112}Sn has been studied. γ-ray excitation functions, ranging from 2.5 to 4.0 MeV, and angular distributions at 2.9 and 3.8 MeV have been measured following the $(\mathrm{n}, \mathrm{n}'\gamma)$ reaction to characterize the decays of the excited levels. Level lifetimes have been measured with the Doppler-shift attenuation method. Low-lying 1^-, (2^-), 3^- and, 5^- states have been identified as members of the heterogeneous quadrupole-octupole quintuplet. Decay properties and excitation energies are consistent with the structure formed by the coupling of the lowest quadrupole, 2_1^+, and octupole, 3_1^-, excitations.

PACS. 21.10.Re Collective levels – 21.10.Tg Lifetimes – 23.20.En Angular distribution and correlation measurements – 25.40.Fq Inelastic neutron scattering

The low-lying structure of nearly spherical nuclei is characterized by collective quadrupole and octupole vibrational modes. The homogeneous and heterogeneous interactions between these modes give rise to mutiphonon quadrupole-quadrupole, octupole-octupole and quadrupole-octupole excitations. In these couplings, the protons and neutrons oscillate in phase. Another kind of excitation can arise as a result of the relative motion of protons and neutrons with respect to each other. These so-called mixed-symmetry states are known in the nearly spherical Mo and Cd nuclei [1,2,3]. Similarly, the low-lying structure in the tin isotopes is expected to show both multi-phonon and mixed-symmetric excitations. In fact, two and three quadrupole phonon states have been identified in ^{124}Sn from $(\mathrm{n}, \mathrm{n}'\gamma)$ experiments [4]. However, there is little information on vibrational excitations in the remainder of the tin isotopes. On the neutron-deficient side of the tin isotopes, ^{112}Sn has been studied from the radioactive decay of ^{112}Sb, inelastic scattering reactions, Coulomb excitation and transfer reactions. The results obtained from these studies are summarized in the NDS compilation [5], where lifetimes of a few states are available and, for a number of states, spins and parities are only tentatively assigned. While the 2^+ (2150.9 keV), 0^+ (2190.8 keV) and 4^+ (2247.4 keV) states in ^{112}Sn have the typical energy pattern of a two-quadrupole-phonon structure, the lack of information on decay properties prevents a precise verification of these assignments. The lifetimes of low-lying states and decay transition rates are crucial for recognizing the different modes of excitation.

It is well known that the nonselectivity of level excitation provided by the $(\mathrm{n}, \mathrm{n}'\gamma)$ reaction at low neutron energies provides a sensitive method for studying low-lying states regardless of their structure [6]. Moreover, since the neutron energy can be kept close to the threshold for a particular excitation, this reaction eliminates the side-feeding effects from the population of higher-lying levels, which otherwise may affect the lifetime determination of the level of interest. Therefore, we have used the $^{112}\mathrm{Sn}(\mathrm{n}, \mathrm{n}'\gamma)$ reaction in order to investigate the low-lying structure of ^{112}Sn. The experiments were carried out at the 7 MV accelerator at the University of Kentucky. A 4 g cylindrical metallic sample with 99.5% enrichment was bombarded with nearly monoenergetic neutrons ($\Delta E \approx 60$ keV), which were produced by the $^3\mathrm{H}(\mathrm{p}, \mathrm{n})^3\mathrm{He}$ reaction. The protons were pulsed at 1.875 MHz with pulse widths of $\approx$ 1 ns. In the angular distribution and excitation function experiments, γ-rays were collected using a BGO Compton-suppressed HPGe detector with a relative efficiency of about 55% and an energy resolution of 2.1 keV (FWHM) at 1332 keV. Excitation functions were performed at incident neutron energies ranging from 2.5 to 4.0 MeV in steps of 0.1 MeV. Angular distributions were carried out at incident neutron energies of 2.9 and 3.8 MeV, at various angles between 40° and 150°, to measure the lifetimes with the Doppler-shift attenuation method (DSAM), as well as to remove ambiguities in spins and parities of previous work. Time-of-flight techniques were used for prompt γ-ray gating in order to suppress time uncorrelated background radiation [6]. In order to confirm the placement of γ-rays in these measurements,

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Table 1. Measured meanlives in the present experiment.

E_x (keV)	J^π	Present	Literaure
1256.68(1)	2_1^+	–	534.0^{+28}_{-29}
2150.85(2)	2_2^+	–	2000^{+700}_{-700}
2190.80(3)	0_2^+	> 650	
2247.37(3)	4_1^+	–	4800^{+900}_{-900}
2354.06(5)	3_1^-	510^{+210}_{-120}	
2720.90(3)	2_4^+	1100^{+1500}_{-400}	
2783.89(6)	4_3^+	440^{+140}_{-90}	
2966.58(5)	2_5^+	660^{+1200}_{-280}	
2969.28(6)	(1,3)	430^{+300}_{-140}	
3092.69(7)	2_6^+	360^{+110}_{-70}	
3133.52(3)	5_1^-	> 1500	
3148.09(5)	4_6^+	820^{+1400}_{-330}	
3272.76(7)	4_7^+	430^{+320}_{-140}	
3286.05(9)	2_8^+	320^{+220}_{-100}	
3383.98(10)	3_2^-	260^{+120}_{-70}	
3397.01(12)	(2^-)	320^{+140}_{-90}	
3433.34(12)	1_1^-	$2.7^{+1.6}_{-1.5}$	
3500.10(10)	(4,5)	64^{+63}_{-30}	
3553.70(12)	(3)	240^{+160}_{-80}	
3610.94(6)	$(2^+, 3^+)$	111^{+60}_{-34}	

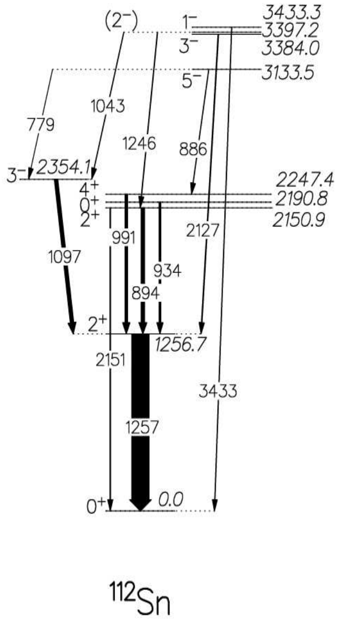

Fig. 1. Partial level scheme of ^{112}Sn showing the quadrupole-octupole coupling.

we also performed a γ-γ coincidence experiment using four HPGe detectors.

Twenty-three new levels have been excited and forty-four new γ-ray observations have occurred. The computer code CINDY, based on the statistical compound nucleus theory of Hasuer-Feshbach-Moldauer [7] was used to calculate the theoretical cross-sections of the excited states. The DSAM requires the energy determination of γ-rays emitted at various angles. The energy of the observed γ-rays, E_γ, at an angle θ with respect to the incident flux direction is given by

$$E_\gamma(\theta) = E_0\Big[1 + F(\tau)\frac{v_{\rm cm}}{c}\cos\theta\Big], \qquad (1)$$

where E_0 is the unshifted γ-ray energy, $v_{\rm cm}$, the maximum recoil velocity of the nucleus in the center-of-mass system, and $F(\tau)$, the Doppler-shift attenuation factor.

In this work, we have precisely determined the meanlives of 15 states (see table 1). The reduced transition probabilities of a number of transitions have been extracted. The $B(E2)$ value for the $2_1^+ \to 0_1^+$ transition is known from previous work [5] to be about 15 W.u., which indicates that there is less collectivity in this nucleus than in the neighbouring Te and Cd nuclei. The 2_2^+ (2150.9 keV), 0_2^+ (2190.8 keV) and 4_1^+ (2247.4 keV) states, decaying to the 2_1^+ state, have nearly twice the excitation energy of the 2_1^+ (1256.7 keV) state and, therefore, are expected to be of two-phonon character. Nevertheless, the measured $B(E2)$ values from 2_2^+, 0_2^+ and 4_1^+ to the 2_1^+ state seem not to support this characterization. The heterogeneous coupling between the lowest quadrupole and octupole states ($2_1^+ \otimes 3_1^-$) gives rise to a quintuplet of states ranging from 1^- to 5^-. These states should lie at an energy roughly equal to the sum of the single-phonon energies, $E(2_1^+) + E(3_1^-)$. Their two-phonon character can be confirmed by the observation of decays either to the 3_1^- state, involving the destruction of the quadrupole phonon, or to the 2_1^+ state, involving the destruction of the octupole phonon. These negative-parity states have been observed in Cd, Ba, Ce, Nd and Sm isotopes. The 1^- states in the Sn isotopes ranging from $A = 116$–124 have been characterized by J. Bryssinck *et al.* [8] as members of the two phonon quadrupole-octupole coupling. Excitation energies and reduced transition probabilities, $B(E1)$, were found to be nearly constant in all these nuclei.

In the present work, we have identified 1^-, (2^-), 3^- and, 5^- states which exhibit excitation energies in the range of 88% to 98% of the energy sum of the 2_1^+ (1256.7 keV) and 3_1^- (2354.1 keV) states. Figure 1 shows a partial level scheme of ^{112}Sn displaying the quadrupole-octupole states. The (2^-) and 5^- states decay to the one-phonon octupole 3_1^- state along with other branchings, whereas the 1^- state decays to the ground state only. The 3^- state of this quintuplet decays to the one-quadrupole phonon 2_1^+ state. Although the observation of two quadrupole phonon excitations are not strongly confirmed, the $2^+ \otimes 3^-$ coupling is evident from the strength of quadrupole phonon decays, which are of the same order as for $B(E2; 2_1^+ \to 0_1^+)$. Hence, the decay properties and excitation energies agree with those expected for the coupling of the quadrupole and octupole phonons.

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