New lifetime measurements in the stable semimagic Sn isotopes using the Doppler-shift attenuation technique

A. Jungclaus[1], J. Walker[1,2], J. Leske[3], K.-H. Speidel[4], A.E. Stuchbery[5], M. East[5], P. Boutachkov[6], J. Cederkäll[7], P. Doornenbal[8], J.L. Egido[2], A. Ekström[7], J. Gerl[6], R. Gernhäuser[9], N. Goel[6], M. Górska[6], I. Kojouharov[6], P. Maier-Komor[9], V. Modamio[1,2], F. Naqvi[6], N. Pietralla[3], S. Pietri[6], W. Prokopowicz[6], H. Schaffner[6], R. Schwengner[10], H.-J. Wollersheim[6]

[1]Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain
[2]Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain
[3]Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany
[4]Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, D-53115 Bonn, Germany
[5]Department of Nuclear Physics, Australian National University, Canberra ACT 0200, Australia
[6]Gesellschaft für Schwerionenforschung (GSI), D-64291 Darmstadt, Germany
[7]Department of Physics, Lund University, S-22100 Lund, Sweden
[8]RIKEN Nishina Center, Wako, Saitama 351-0198, Japan
[9]Physik Department E12, Technische Universität München, D-85748 Garching, Germany
[10]Institut für Kern- und Hadronenphysik, FZ Rossendorf, D-01314 Dresden, Germany

E-mail: `andrea.jungclaus@iem.cfmac.csic.es`

Abstract. Precise measurements of lifetimes in the picosecond range of excited states in the stable even-A Sn isotopes ^{112,114,116,122}Sn have been performed using the Doppler shift attenuation technique. For the first excited 2^+ states in ^{112}Sn, ^{114}Sn and ^{116}Sn the $E2$ transition strengths deduced from the measured lifetimes are in disagreement with the previously adopted values. They indicate a shallow minimum at $N = 66$ in contrast to the maximum at mid-shell predicted by modern shell model calculations.

The chain of semi-magic tin isotopes occupies an exceptional position in nuclear structure research. With the 33 experimentally accessible isotopes between the two double-magic cornerstones ^{100}Sn and ^{132}Sn, it allows for systematic and stringent tests of the validity of nuclear structure models across an entire span of a large major neutron shell, from the proton dripline with $N = Z$ to the isotope which has eight neutrons more than the most neutron-rich stable tin isotope. While the regions around the double-magic isotopes are of fundamental importance for the understanding of the nuclear structure far away from the valley of stability [1, 2, 3] the possibility to follow quantities such as excitation energies and transition strengths over a large range of neutron to proton ratios, namely $N/Z = 1.0 - 1.64$, enables the scrutiny of basic concepts in nuclear structure physics.

There is a general understanding that the collectivity in atomic nuclei is highest when the number of nucleons outside closed shells is largest, i.e. around mid-shell. A formal rationale

for this general rule is provided by the seniority scheme, which supplies an exact solution to the simple pairing Hamiltonian for one single j-shell. It predicts a constant excitation energy for the first excited 2^+ state and a parabolic behavior with the maximum value at mid-shell of the transition probabilities to these first-excited 2^+ states, $B(E2; 0^+_{\text{g.s.}} \to 2^+_1)$ (in the following abbreviated as $B(E2)$), as a function of the number of particles in this j-shell [4]. Some features of this simple seniority model remain effective even when it is generalized by considering several j orbitals and more realistic interactions [4]. Because of the strong pairing correlations along the tin isotopic chain, it has long been considered as a good example for the approximate validity of the generalized seniority scheme. Indeed, the energy of the first excited 2^+ state is near constant across the entire major $N = 50 - 82$ neutron shell and at least in its upper half the $B(E2)$ values decrease with increasing neutron number from the mid-shell nucleus ^{116}Sn toward the $N = 82$ shell closure following a smooth parabolic behavior as described also by seniority truncated large scale shell model calculations [5, 6, 7] .

In recent years, however, a series of experiments have examined the $E2$ strength in the Sn isotopes with A=106-114, in the lower half of the major neutron shell [7, 8, 9, 10, 11, 12, 13]. In these studies on stable and neutron-deficient isotopes, a sudden increase in $E2$ strengths has been observed between the mid-shell isotope ^{116}Sn and its neighbor ^{114}Sn, with the values then staying nearly constant within the experimental uncertainties down to ^{106}Sn. This behavior contrasts with predictions from modern large-scale shell model calculations [7].

The measured $E2$ transition strengths in the stable even-A Sn isotopes are mainly based on Coulomb excitation experiments while information from direct lifetime measurements is scarce. We have measured the lifetimes of the first excited 2^+ states as well as some higher-lying states in the stable even-A Sn isotopes with A=112,114,116,122 using the Doppler-shift attenuation (DSA) method in order to provide an independent proof of the observed discontinuity in the $B(E2)$ systematics between ^{114}Sn and ^{116}Sn.

Two new experiments, with virtually identical experimental setups, were performed at the UNILAC accelerator of the Gesellschaft für Schwerionenforschung (GSI). Beams of ^{112,114,116}Sn at 4.0 MeV/u were used in the first run and a 3.8 MeV/u ^{122}Sn beam was used in the second. Besides the lifetime measurement we were aiming to determine the magnetic moments of the 2^+_1 states using the transient field technique (the magnetic moment results will be presented elsewhere [14]); the beam particles therefore impinged on multilayer targets consisting of 0.67 mg/cm^2 (0.66 mg/cm^2 in the ^{122}Sn run) natural C, 10.8 (10.9) mg/cm^2 natural Gd, 1.0 (1.0) mg/cm^2 Ta and finally a 4.86 (5.23) mg/cm^2 Cu layer. A thick Ta foil was mounted behind the target to stop the beam. Four Si diodes (1cm x 1cm each) were placed 30 mm (27 mm) downstream above and below the beam axis to detect the forward scattered C target ions in the vertical angular ranges of 2°-20° and 23°-38°. The γ rays emitted from the excited states populated in the Coulomb excitation of the Sn projectiles on the C target layer were detected in coincidence with the C ions in four EUROBALL cluster detectors positioned in a horizontal plane at angles of $\pm 65°$ and $\pm 115°$ with respect to the beam axis at a distance of 24 cm (22 cm) from the target. Each of the cluster detectors consists of seven individual Ge crystals, which for the lineshape analysis have been combined into groups according to their average polar angle with respect to the beam. For the lifetime determination the spectra obtained with the detectors positioned at 53°, 65°, 115° and 127° to the beam axis have been analyzed because at these angles the lineshapes are most sensitive to the lifetime value. A sketch of the experimental setup is shown in Fig. 1.

Besides the Coulomb excitation of the Sn beams on the carbon layer of the multilayer target, also the alpha transfer reaction from Sn to Te is observed in our experiments as evidenced by a second peak at lower energy in the spectra of the Si detectors. By applying coincidence gates on either peak clean γ ray spectra are obtained for both the Coulomb excitation as well as the
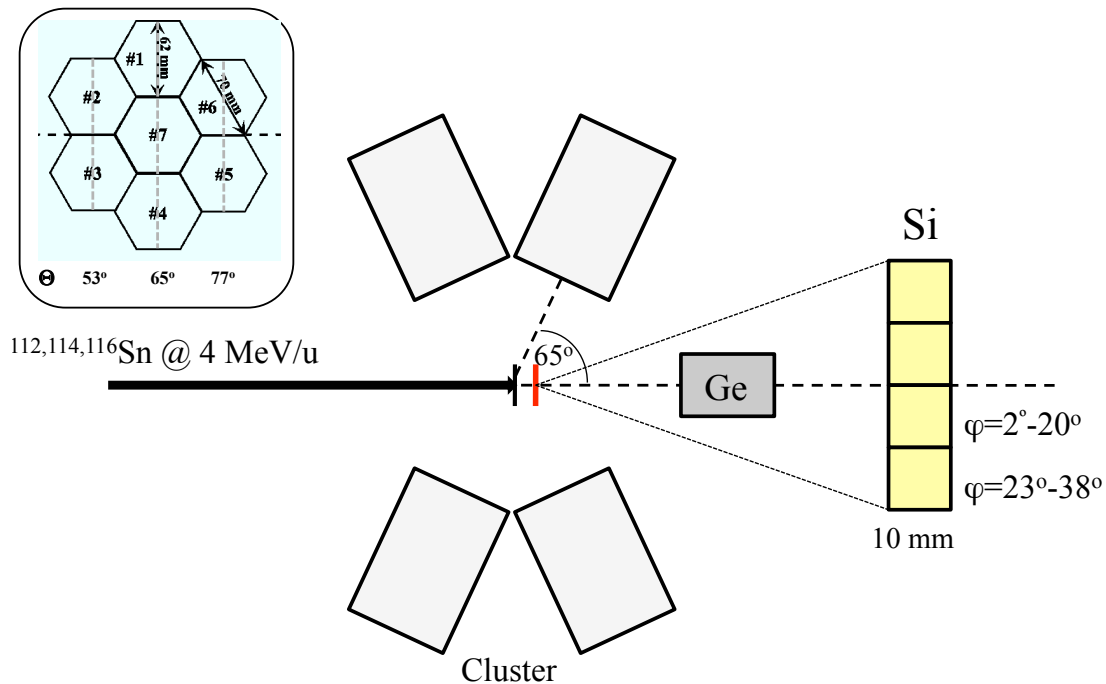
Figure 1. Sketch of the experimental setup used in the experiments performed at GSI. The γ radiation is detected in four EUROBALL cluster detectors positioned at $\pm 65°$ and $\pm 115°$ with respect to the beam axis in coincidence with charged particles detected in an array of four Si diodes.

alpha tranfer channel as demonstrated in Fig. 2 for the case of a ^{114}Sn beam, in which the decay of excited states in ^{114}Sn and ^{118}Te is observed. While all lines in the ^{118}Te spectrum are narrow indicating lifetimes above a picosecond for all decaying states, the $2_1^+ \rightarrow 0^+$ and $3_1^- \rightarrow 2_1^+$ transitions in ^{114}Sn clearly show Doppler-shifted lineshapes.

To analyze these observed Doppler-broadened lineshapes and extract the lifetime information we modified the LINESHAPE program package [15] in order to (i) evaluate the kinematics of the Coulomb excitation reaction, taking into account the non-cylindrical geometry of the particle detectors, (ii) take into account the structure of the multilayer targets, and (iii) include angular correlation effects. For the description of the slowing-down process the stopping powers of Ziegler *et al.* [16] were used.

For each transition of interest eight different experimental lineshapes corresponding to the combinations of the four γ-ray detection angles with the two pairs of Si detectors covering different angular ranges have been analyzed. As an example of the lineshape analysis, Fig. 3 shows the fits obtained for the $3_1^- \rightarrow 2_1^+$ transition in ^{114}Sn in the spectra taken at $53°$ and $65°$ to the beam axis in coincidence with C ions detected in the inner pair of Si detectors. It is noteworthy that the lifetimes of the 3_1^- states determined in the present work are in good agreement with the literature values available in the cases of ^{116}Sn and ^{122}Sn [19, 20].

For the determination of the lifetimes of the first excited 2^+ states feeding from the higher states, mainly from the 4_1^+ and 3_1^- levels (compare Fig. 2), has to be taken into account in the analysis of the lineshapes. For each isotope under study the feeding intensities were determined from the γ ray spectra taking into account angular correlation effects. This observed feeding, which amounts to 5-15 % from the 4_1^+ and 15-30 % from the 3_1^- levels, respectively, has been included in the fits to the lineshapes of the $2_1^+ \rightarrow 0^+$ transitions. While the 4_1^+ states are too long lived to show a significant Doppler shifted fraction, for the feeding from the 3_1^- states the
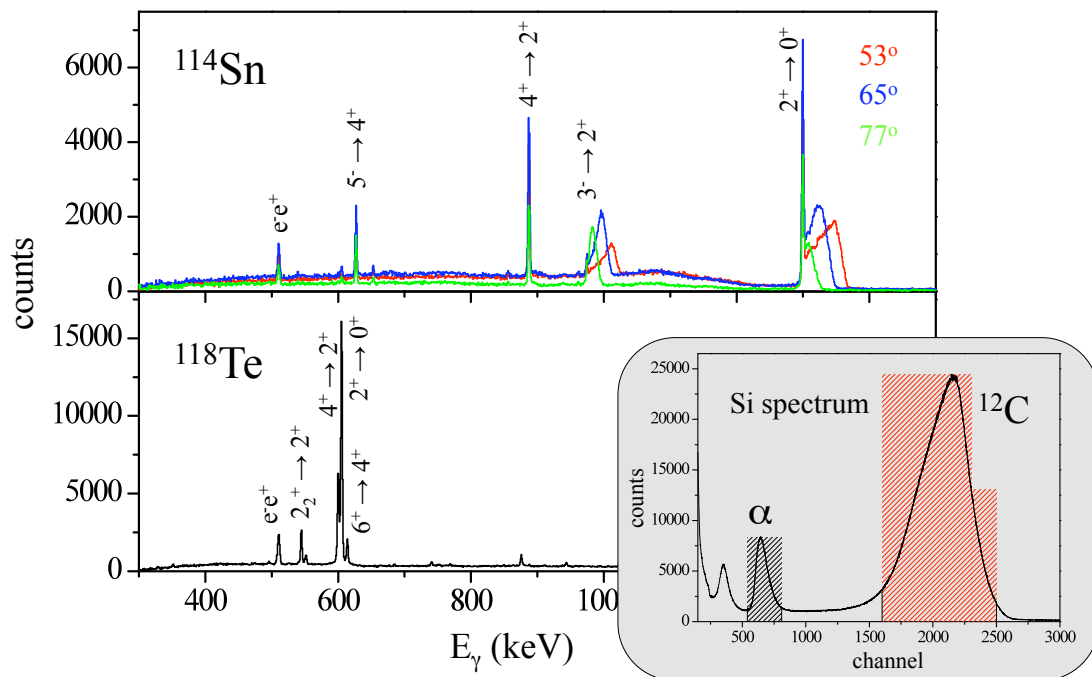
Figure 2. γ ray spectra for ^{114}Sn and ^{118}Te obtained in coincidence with carbon ions and alpha particles, respectively, detected in the inner pair of Si detectors during the run with a ^{114}Sn beam.

lifetimes obtained from the fit of the lineshapes of the $3^-_1 \rightarrow 2^+_1$ transitions in the present work (see Fig. 3) have been employed.

Additional feeding from other higher-lying states into the 2^+ states of interest cannot be excluded considering that beam energies above the Coulomb barrier were used in the present experiments. To account at least in a global way for such a possible unobserved feeding, the intensities of both the $4^+_1 \rightarrow 2^+_1$ as well as $3^-_1 \rightarrow 2^+_1$ feeding transitions were varied independently by $\pm 20\%$ and the resulting variation of the deduced 2^+_1 lifetime was added to the statistical error. Final lifetime values were obtained as weighted means of the eight individual fit results. Uncertainties in the stopping power description of about 5% have been considered in the determination of the quoted error.

To test the robustness of the lifetime results we performed a number of checks using ^{114}Sn as example. To test the importance of an exact knowledge of the thicknesses of the various target layers, the thickness of the Gd and Ta layers were varied independently by $\pm$ 0.5 mg/cm^2. The obtained lifetime values were all within 0.01 ps with the best fits obtained for the nominal thicknesses. This observed independence of the fitted lifetime on the Gd and Ta thicknesses is expected since the decay of the 2^+_1 state in most cases takes place well before the recoiling Sn ion reaches the Gd-Ta interface. And whenever the 2^+_1 state had been populated from the long-lived 4^+_1 state it decays after the ion has been completely stopped in the Cu layer. This means that possible variations of the layer thicknesses have no influence on the obtained lifetimes. In a second step we varied the region of the lineshape considered in the fit. Choosing only the region of largest Doppler shifts corresponds to selecting the highest recoil velocities and the first layer of the backing. However, no changes in the resulting lifetime values were found (variations within 0.01 ps) for many different widths and positions of the fit region. Finally, to check the influence of the choice of the stopping power used in the lineshape analysis on the resulting lifetime values the analysis was repeated by replacing the Ziegler stopping powers with those of
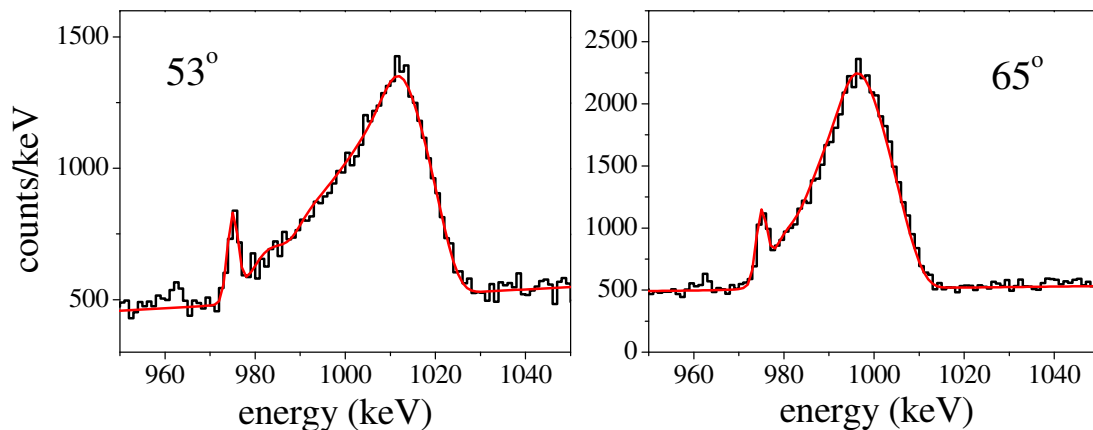
Figure 3. Lineshape fits for the $3_1^- \rightarrow 2_1^+$ transition in ^{114}Sn observed in the Ge crystals at the designated polar angles with respect to the beam axis, in coincidence with C ions.

Northcliffe-Schilling (NS) [17]. The resulting lifetimes were again within 0.01 ps which indicates that for Gd as stopping material and the large recoil velocities relevant in this analysis both parametrizations are very similar. For a more detailed discussion of the full analysis procedure we refer the reader to a forthcoming publication [18].

Directly measured lifetime values for the 2_1^+ states are now available for the stable even-A Sn isotopes with A=112,114,116,122. Comparing the $B(E2)$ values derived from these lifetimes to the literature values [5, 12, 13] systematically lower values were found in all cases. We emphasize here the robustness of the new data, particularly for revealing systematic trends, and also the absolute values. In ^{116}Sn, our present value is about 20% smaller than the adopted value of 0.209(6) e^{2}b^2 [5]. Also, for the $B(E2)$ in ^{112}Sn and ^{114}Sn the observed difference is of the order of 20%. However, remembering that the $B(E2)$ values in ^{112,114}Sn have been deduced in Refs. [12, 13] relative to an adopted value for ^{116}Sn, it is interesting to note that renormalization to our new $B(E2)$ value for ^{116}Sn leads to values of $B(E2)$=0.195(8) e^{2}b^2 and $B(E2)$=0.186(8) e^{2}b^2 for ^{112}Sn and ^{114}Sn, respectively, which are then in excellent agreement with our values. Coming back to the conflicting case of ^{116}Sn, it is interesting to note that the adopted B(E2) value quoted in [5] is based on fifteen individual measurements (ranging from 0.145(21) to 0.29(6) e^{2}b^2) performed between 1957 and 2000 using Coulomb excitation, nuclear resonance fluorescense or electron scattering. While our new values deduced from the measured lifetimes overlap within the experimental uncertainties with eight of them, they clearly deviate from the values obtained in Coulomb excitation experiments, which have the smallest quoted error bars, namely 0.216(5) e^{2}b^2, 0.195(7) e^{2}b^2 and 0.223(13) e^{2}b^2 [21, 22, 23], and which dominate the adopted value.

Unfortunately only in two cases, ^{112}Sn and ^{114}Sn, measurements of the 2_1^+ lifetime using Doppler techniques have been reported in the literature. Using the (n,n'γ) reaction and the DSA method, Orce et al. obtained a value of $\tau(2_1^+)$=0.750($^{+125}_{-90}$) ps in ^{112}Sn which later on was corrected to $\tau(2_1^+)$=0.535($^{+100}_{-80}$) ps [10]. Note that, in contrast with the present DSA measurements, those in Ref. [10] have a very low recoil velocity and the measured average Doppler shift is insensitive to the nuclear lifetime. In ^{114}Sn the Cologne group measured $\tau(2_1^+)$=0.56(11) ps performing a DDCM (differential decay curve method) coincidence analysis of plunger data [24]. Finally, a DSA value of $\tau(2_1^+)$=0.45(15) ps has been reported for ^{114}Sn in Ref. [25]. All these values agree within the experimental uncertainties with the results of our present work.

A full account of our new experimental results and their comparison to theoretical calculations [7, 11, 26, 27, 28] will be given elsewhere [18, 29]. However, our new results seem to indicate a local minimum at $N = 66$ followed by a smooth increase between ^{116}Sn and ^{112}Sn in contrast to the behaviour of the literature and adopted values.

In conclusion, we discussed new lifetime measurements in the stable even tin isotopes ^{112,114,116,122}Sn performed using Doppler shift techniques in combination with Coulomb excitation in inverse kinematics. We hope that our new experimental results for the stable Sn isotopes will stimulate new theoretical studies as well as new experiments to improve and extend the $B(E2)$ measurements on the neutron-deficient radioactive isotopes. In light of the observed discrepancies between the results of the present work and literature values the realization of new optimized measurements of $B(E2)$ values in ^{114,116}Sn using both Coulomb excitation as well as direct lifetime techniques in combination with powerful experimental setups is certainly highly desirable.

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