Nuclear structure in the neutron-deficient Sn nuclei

TKEL effects on lifetime measurements

Marco Siciliano[1,2,*], *José-Javier* Valiente-Dobón[2], and *Alain* Goasduff[3,4]

[1]Irfu/CEA, Université de Paris-Saclay, Gif-sur-Yvette, France.
[2]INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy.
[3]Dipartimento di Fisica e Astronomia, Università di Padova, Padova, Italy.
[4]INFN, Sezione di Padova, Padova, Italy.

Abstract. The presence of seniority-like isomers along the $Z = 50$ isotopic chain have been an experimental limitation to the investigation of the electromagnetic properties of the low-lying states in the light Sn nuclei. Combining a multi-nucleon transfer reaction with the Recoil-Distance Doppler-Shift technique, the lifetimes of the 2_1^+ and 4_1^+ excited states have been directly measured in the neutron-deficient ^{106,108}Sn isotopes for the very first time. The emitted γ rays were detected by the AGATA array, while the reaction products were uniquely identified by the VAMOS++ magnetic spectrometer. The control of the direct feeding of the states by gating on the Total Kinetic Energy Loss, together with the unique capabilities of the two spectrometers, was crucial for the measurement in ^{108}Sn.

1 Introduction

The investigation of nuclear structure close to $Z = 50$ shell closure have been a hot and discussed topic for both theoretical and experimental groups. The Sn region is the longest isotopic chains between two experimentally accessible neutrons shell closures, namely $N = 50$ and $N = 82$. Hence, it provides a unique opportunity for systematic studies of the evolution of basic nuclear properties when going from very neutron-deficient to very neutron-rich species.

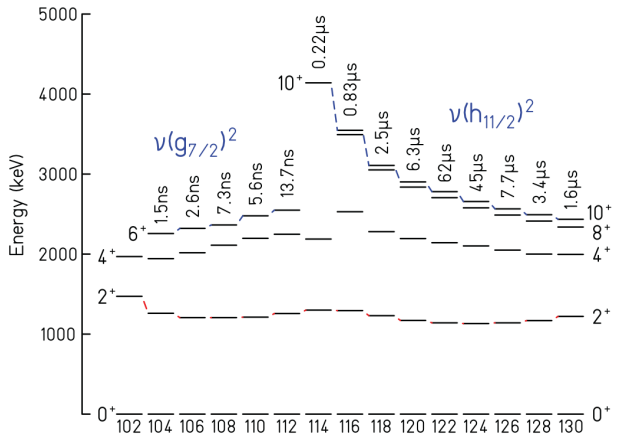

Figure 1. Excitation energy of the low-lying states along the Sn isotopic chain. The rather constant energy of the 2_1^+ and 4_1^+ excited states and the low-lying isomers, whose features can be attributed to seniority isomers, suggest the presence of pairing dominance. Adapted from Ref. [1].

In this context, the Sn nuclei have been considered a paradigm of pairing dominance. As shown in Fig. 1, the excitation energies of the first 2^+ and 4^+ states are rather constant along the Sn isotopic chain, while the low-lying isomeric states have features in common with seniority isomers due to the break of a $g_{7/2}$ and a $h_{11/2}$ neutron pair for the neutron-deficient and neutron-rich isotopes, respectively. Moreover, for isotopes with $A > 116$ the $B(E2; 2_1^+ \rightarrow 0_1^+)$ values present a parabolic behavior, that is expected for the seniority scheme. On the other hand, as presented in Fig. 2, for the lighter Sn nuclei, experimental results on transition probabilities are scarce. In fact, such a neutron-deficient region cannot be investigated with the typical combination of fusion-evaporation reactions with lifetime measurement because of the presence of low-lying isomeric states, which hindered direct measurements of lifetimes below them. Only with the advent of radioactive ion-beam facilities, Coulomb-excitation measurements have allowed to extract the reduced transition probabilities between the first excited 2^+ state and the ground state [1–8]. Within experimental uncertainties, the results suggest a rather-constant behavior for $106 \leq A \leq 110$, instead of the expected parabolic trend. Unfortunately, the lack of information on the $B(E2; 4_1^+ \rightarrow 2_1^+)$ strengths in light Sn nuclei [9], combined with large experimental uncertainties on the $B(E2; 2_1^+ \rightarrow 0_1^+)$ values, prevents firm conclusions on the shell evolution in the vicinity of the heaviest proton-bound $N = Z$ doubly-magic nucleus ^{100}Sn.

To remedy such an experimental limitation, the first lifetime measurement in neutron-deficient Sn isotopes was carried out using the Recoil Distance Doppler-Shift (RDDS) technique, providing a complementary informa-

*e-mail: marco.siciliano@cea.fr

tion to the previous Coulomb-excitation studies. Thanks to the unusual application of a Multi-Nucleon Transfer (MNT) reaction, that is commonly used to investigate neutron-rich nuclei [20–22], together with unprecedented capabilities of the powerful AGATA and VAMOS++ spectrometers, the lifetimes of the 2_1^+ and 4_1^+ states in ^{106,108}Sn have been directly measured for the very first time [23]. The employment of a MNT reaction not only allowed to directly populate the excited states below the isomers, but permitted also to control such a feeding by an appropriate gate on the Total Kinetic Energy Loss (TKEL) [24, 25].

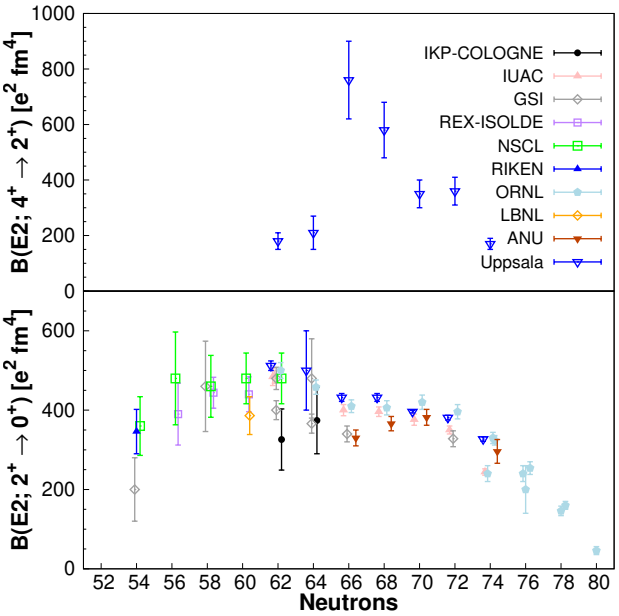

Figure 2. Experimental reduced transition probabilities $B(E2)$ for the (top) $4_1^+ \rightarrow 2_1^+$ and (bottom) $2_1^+ \rightarrow 0_1^+$ transitions along the Sn isotopic chain. Data taken from Refs. [1–19].

In this contribution the features of this unconventional procedure are investigated by showing the effects of the TKEL gate on the lifetime measurements.

2 Experiment

The light Sn isotopes were obtained in the collision of a ^{106}Cd beam, provided by the separated-sector cyclotron of the GANIL facility at an energy of 770 MeV, and a 0.7 mg/cm^2 ^{92}Mo. The lifetime measurement was performed with the Recoil Distance Doppler-Shift (RDDS) technique [26, 27] by mounting the target and a 1.6 mg/cm^2 thick ^{nat}Mg degrader on the differential Cologne plunger. The complete (A,Z) identification of the projectile-like reaction products was obtained on an event-by-event basis using the VAMOS++ spectrometer [28, 29]. In coincidence with the magnetic spectrometer, the γ rays were detected by the AGATA array [30, 31], consisting of 8 triple-cluster detectors placed at backward angles. More details about the ion identification and the analysis procedure can be found in Refs. [23, 32, 33].

Thanks to the fine position sensitivity of both the spectrometers, Doppler correction was applied on an event-by-event basis. Such a sensitivity was essential for performing the measurement because for each γ-ray transition two peaks were observed, related to its emission before and after the Mg foil. The γ rays emitted after the degrader are properly Doppler corrected (I_u), while those emitted before are shifted to lower energies (I_s) because of the different velocity of the reaction fragment. The relative intensities of the peaks area as a function of the target-degrader distance are related to the lifetime of the state of interest [26, 27].

3 Results

Thanks to the simultaneous measurement of the angle (θ_{bl}) and of the energy (E_{bl}) of the beam-like reaction fragments entering in VAMOS++, the TKEL of the reaction can be extracted under the assumption of a binary reaction without particle evaporation. For the reconstruction it was assumed, that the reaction occurs in the centre of the target: the energy of the beam ion at the centre of the target (E_r) was calculated by taking into account the energy loss in the ^{92}Mo material and the same procedure was adopted to calculate the energy E_{bl} at the centre of the target. The TKEL of the reaction was obtained by using the non-relativistic formula [34]

$$TKEL = \frac{m_{tl} - m_b}{m_{tl}} E_r - \frac{m_{tl} + m_{bl}}{m_{tl}} E_{bl} + \frac{2}{m_{tl}} \sqrt{m_b m_{bl} E_r E_{bl}} \cos\theta_{bl} \quad (1)$$

where m_t, m_{tl} and m_{bl} are the target, the target-like and beam-like masses respectively.

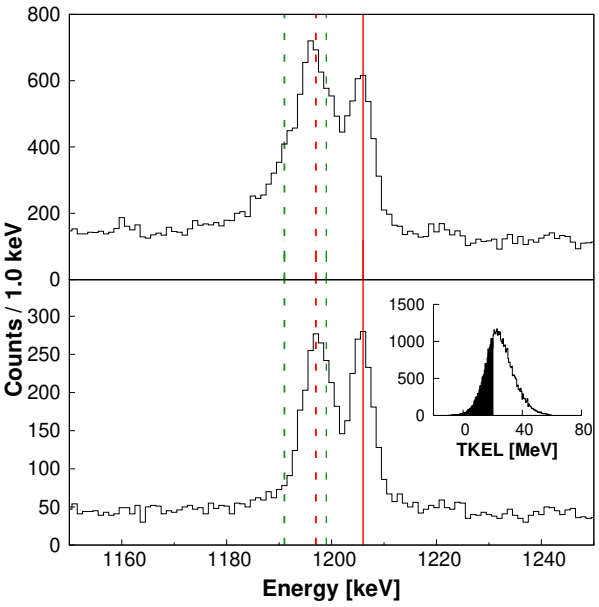

Figure 3. Doppler-corrected γ-ray energy spectra of ^{108}Sn with (bottom) and without (top) the TKEL≤ 21 MeV condition, obtained by summing up the statistics of all the distances. The shifted (dashed lines) and unshifted (solid lines) components of $8_1^+ \rightarrow 6_1^+$ (green) and $2_1^+ \rightarrow 0_1^+$ (red) are marked. In the inset the TKEL distribution and the required condition are shown.

For the lifetime measurement of the low-lying states in ^{108}Sn, the adoption of the TKEL-gate procedure was crucial. Indeed, as shown in the spectra of Fig. 3, for this nucleus the energies of $8^+_1 \rightarrow 6^+_1$ and $2^+_1 \rightarrow 0^+_1$ transitions are very similar and their different components cannot be distinguished, so traditional methods cannot be used to measure the lifetime of the 2^+_1 state. However, since the population of higher (lower) excited states in the final nucleus correspond to higher (lower) values of TKEL, it is possible to reduce the population of the excited states above the 6^+ isomer by imposing the TKEL$\leq$ 21 MeV condition: the two peaks related to the $8^+_1 \rightarrow 6^+_1$ transition became negligible. Such a procedure allowed us to take into account just the 6^+_1, 4^+_1 and 2^+_1 states in the lifetime measurement via the Decay-Curve Method [23].

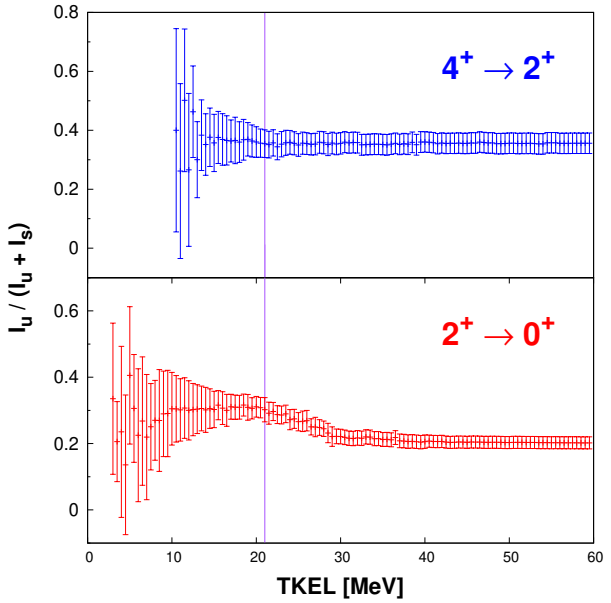

Figure 4. Decay curve ratio as a function of the TKEL-gate upper limit for the $4^+_1 \rightarrow 2^+_1$ and $2^+_1 \rightarrow 0^+_1$ transitions of ^{108}Sn. The values are obtained by summing up all the spectra obtained for the different distances. The defined threshold of the TKEL is shown with a purple solid line.

The 21 MeV upper limit was obtained via a systematic investigation on the effects of the TKEL-gate on the decay curve, displayed in Fig. 4: the threshold was chosen in order to minimize the area of the $8^+_1 \rightarrow 6^+_1$ transition peaks until they become negligible and the measured lifetime of the 2^+_1 excited state, here shown as the $I_u/(I_u + I_s)$ ratio, remained constant even for more restricted conditions. In fact, for the $2^+_1 \rightarrow 0^+_1$ transition the ratio slightly increases from 0.20 to 0.31 and then remain constant for lower TKEL values. For the $4^+_1 \rightarrow 2^+_1$ transition, instead, the ratio is practically independent on the TKEL gate and this is due to the presence of the 6^+ state: reducing the population of the higher-spin states does not affect the lifetime of the 4^+_1 excited states, since their feeding is anyway blocked by the presence of the isomer. Moreover, in Fig. 4 one should also notice that for TKEL$\approx$ 12 MeV the population of the 4^+_1 state starts to be not sufficient for measuring the lifetime, causing the evident fluctuations in the ratio; for the 2^+_1 state, instead, the fluctuations start around TKEL$\approx$ 7 MeV and the intensities ratio slightly decrease with very restrictive conditions. This is a clear example of the sensitivity of the technique for the used reaction: the gate on the reconstructed TKEL is capable to reduce so much the population of the 4^+_1 state, whose excitation energy is 905 keV larger than the one of the 2^+_1 state, that its feeding becomes negligible, making the effective lifetime of the 2^+_1 state shorter. Unfortunately, for such a restrictive condition, the statistics in the $2^+_1 \rightarrow 0^+_1$ transition components was not sufficient to perform the lifetime measurement.

4 Conclusion

In this work deep-inelastic collisions, in the specific multi-nucleon transfer reactions, have shown to be a powerful tool to investigate not only the neutron-rich nuclei but also the neutron-deficient species. Indeed, the employment of a multi-nucleon transfer reaction with the plunger device allowed to investigate the electromagnetic properties of the low-lying states close to ^{100}Sn, overcoming the experimental limitations caused by the presence of low-lying isomers. Moreover, thanks to the combination of such technique with the capabilities of both the AGATA and VAMOS++ spectrometers, the Total Kinetic Energy Loss can be reconstructed and then used to control the feeding from higher-lying states, simplifying the considered decay cascade while measuring the lifetime with the Decay Curve Method.

References

[1] R. Kumar, P. Doornenbal, A. Jhingan, R.K. Bhowmik, S. Muralithar, S. Appannababu, R. Garg, J. Gerl, M. Górska, J. Kaur et al. Physical Review C **81**, 024306 (2010).

[2] A. Banu, J. Gerl, C. Fahlander, M. Górska, H. Grawe, T. R. Saito, H.-J. Wollersheim, E. Caurier, T. Engeland, A. Gniady et al. Physical Review C **72**, 061305(R) (2005).

[3] C. Vaman, C. Andreoiu, D. Bazin, A. Becerril, B.A. Brown, C. M. Campbell, A. Chester, J.M. Cook, D.C. Dinca, A. Gade et al. Physical Review Letters **99**, 162501 (2007).

[4] J. Cederkäll, A. Ekström, C. Fahlander, A.M. Hurst, M. Hjorth-Jensen, F. Ames, A. Banu, P.A. Butler, T. Davinson, U. Datta Pramanik et al. Physical Review Letters **98**, 172501 (2007).

[5] A. Ekström, J. Cederkäll, C. Fahlander, M. Hjorth-Jensen, F. Ames, P.A. Butler, T. Davinson, J. Eberth, F. Fincke, A. Görgen et al. Physical Review Letters **101**, 012502 (2008).

[6] V.M. Bader, A. Gade, D. Weisshaar, B.A. Brown, T. Baugher, D. Bazin, J.S. Berryman, A. Ekström, M. Hjorth-Jensen, S.R. Stroberg et al. Physical Review C **88**, 051301(R) (2013).

[7] P. Doornenbal, S. Takeuchi, N. Aoi, M. Matsushita, A. Obertelli, D. Steppenbeck, H. Wang, L. Audirac,

H. Baba, P. Bednarczyk et al. Physical Review C **90**, 061302(R) (2014).

[8] R. Kumar, M. Saxena, P. Doornenbal, A. Jhingan et al. Physical Review C **96**, 054318 (2017).

[9] N. Jonsson, A. Bäcklin, J. Kantele, R. Julin, M. Luontama, A. Passoja. Nuclear Physics A **371**, 333 (1981).

[10] D.C. Radford et al. Nuclear Physics A **746**, 83 (2004).

[11] J.N. Orce, S.N. Choudry, B. Crider, E. Elhami, S. Mukhopadhyay, M. Scheck, M.T. McEllistrem, S.W. Yates. Physical Review C **76**, 021302(R) (2007).

[12] P. Doornenbal, P. Reiter, H. Grawe, H. J. Wollersheim, P. Bednarczyk, L. Caceres, J. Cederkäll, A. Ekström, J. Gerl, M. Górska et al. Physical Review C **78**, 031303(R) (2008).

[13] J.M. Allmond, D.C. Radford, C. Baktash, J.C. Batchelder, A. Galindo-Uribarri, C.J. Gross, P.A. Hausladen, K. Lagergren, Y. Larochelle, E. Padilla-Rodal et al. Physical Review C **84**, 061303(R) (2011).

[14] A. Jungclaus, J. Walker, J. Leske, K.H. Speidel, A.E. Stuchbery, M. East et al. Physics Letters B **695**, 110 (2011).

[15] G. Kumbartzki et al. Physical Review C **86**, 034319 (2012).

[16] G. Guastalla, D.D. Di Julio, M. Górska, J. Cederkäll, P. Boutachkov, P. Golubev, S. Pietri, H. Grawe, F. Nowacki, K. Sieja et al. Physical Review Letters **110**, 172501 (2013).

[17] J.M. Allmond, A.E. Stuchbery, A. Galindo-Uribarri, E. Padilla-Rodal, D.C. Radford, J.C. Batchelder, C.R. Bingham, M.E. Howard, J.F. Liang, B. Manning et al. Physical Review C **92**, 041303(R) (2015).

[18] G.J. Kumbartzki, N. Benczer-Koller, K.-H. Speidel, D.A. Torres, J.M. Allmond, P. Fallon, I. Abramovic, L.A. Bernstein, J.E. Bevins, H.L. Crawford et al. Physical Review C **93**, 044316 (2016).

[19] M. Spieker, P. Petkov, E. Litvinova, C. Müller-Gatermann, S. G. Pickstone, S. Prill, P. Scholz, A. Zilges. Physical Review C **97**, 054319 (2018).

[20] S. Szilner, C. A. Ur, L. Corradi, N. Mărginean, G. Pollarolo, A. M. Stefanini, S. Beghini, B.R. Behera, E. Fioretto, A. Gadea et al. Physical Review C **76**, 024604 (2007).

[21] L. Corradi, G. Pollarolo, and S. Szilner. Journal of Physics G **36**, 113101 (2009).

[22] J.J. Valiente-Dobón. Basic Concepts in Nuclear Physics: Theory, Experiments and Applications **182**, 87 (2016).

[23] M. Siciliano, J.J. Valiente-Dobón, A. Goasduff, F. Nowacki, A.P. Zuker. arXiv:1905.10313v2 (2019).

[24] J.J. Valiente-Dobón, D. Mengoni, A. Gadea, E. Farnea, S.M. Lenzi, S. Lunardi, A. Dewald, T. Pissulla, S. Szilner, R. Broda et al. Physical Review Letters **102**, 242502 (2009).

[25] D. Mengoni, J.J. Valiente-Dobón, E. Farnea, A. Gadea, A. Dewald, A. Latina. European Physics Journal A **42**, 387 (2009).

[26] A. Dewald, S. Harissopulos, and P. Von Brentano. Zeitschrift für Physik A **334**, 163 (1989).

[27] A. Dewald, O. Möller, P. Petkov. Progress in Particle and Nuclear Physics **67**, 786 (2012).

[28] S. Pullanhiotan, A. Chatterjee, B. Jacquot, A. Navin, M. Rejmund. Nuclear Instruments and Methods in Physics Research B **266**, 4148 (2008).

[29] M. Rejmund, B. Lecornu, A. Navin, C. Schmitt et al. Nuclear Instruments and Methods in Physics Research A **646**, 184 (2011).

[30] S. Akkoyun et al., Nuclear Instruments and Methods in Physics Research A **668**, 26 (2012).

[31] E. Clément, C. Michelagnoli, G. de France, H. J. Li, A. Lemasson, C. B. Dejean, et al. Nuclear Instruments and Methods in Physics Research A **855**, 1 (2017).

[32] M. Siciliano, J. J. Valiente-Dobón, A. Goasduff, D. Bazzacco et al. Acta Physica Polonica B **48**, 331 (2017).

[33] M. Siciliano. Nuovo Cimento C **40**, 84 (2017).

[34] A.B. Brown, C.W. Snyder, W.A. Fowler and C.C. Lauritsen. Physical Review **82**, 159 (1951).