PAPER • **OPEN ACCESS**

Core-proton coupled nature of the $11/2^+$ state in ^{131}Sb probed by lifetime measurements

To cite this article: S. Bottoni *et al* 2023 *J. Phys.: Conf. Ser.* **2453** 012028

View the article online for updates and enhancements.

You may also like

- Robust matrices in the interval max-plus algebra
Siswanto, Pangadi and S B Wiyono
- R+RG gravity with maximal Noether symmetry
Yu E Pokrovsky
- Lifetime measurements of the low-lying excited states of ^{208}Po
D. Kocheva, A. Yaneva, D. Kalaydjieva et al.

This content was downloaded from IP address 159.149.103.6 on 26/05/2023 at 23:53

Core-proton coupled nature of the $11/2^+$ state in ^{131}Sb probed by lifetime measurements

S. Bottoni[1,2], E. R. Gamba[1,2], G. De Gregorio[3,4], A. Gargano[4], S. Leoni[1,2], B. Fornal[5], N. Brancadori[1], G. Ciconali[1,2], F. C. L. Crespi[1,2], N. Cieplicka-Oryńczak[5], Ł. W. Iskra[5], G. Colombi[1,2,6], Y.H. Kim[6]†, U. Köster[6], C. Michelagnoli[6], F. Dunkel[7], A. Esmaylzadeh[7], L. Gerhard[7], J. Jolie[7], L. Knafla[7], M. Ley[7], J.-M. Régis[7], K. Schomaker[7], M. Sferrazza[8]

[1]Dipartimento di Fisica, Università degli Studi di Milano, 20133 Milano, Italy
[2]INFN Sezione di Milano, 20133, Milano, Italy
[3]Dipartimento di Matematica e Fisica, Università degli Studi della Campania "Luigi Vanvitelli," 81100 Caserta, Italy
[4]INFN Sezione di Napoli, 80126, Napoli, Italy
[5]Institute of Nuclear Physics, PAN, 31-342 Kraków, Poland
[6]Institut Laue-Langevin, 38042 Grenoble, France
[7]Universität zu Köln, Institut für Kernphysik, 50937 Köln, Germany
[8]Département de Physique, Université libre de Bruxelles, 1050 Bruxelles, Belgium

E-mail: simone.bottoni@mi.infn.it

Abstract. The structure of the $11/2^+_1$ state in ^{131}Sb was investigated at the LOHENGRIN spectrometer of Institut Laue-Langevin via neutron-induced fission of ^{235}U and lifetime measurements, yielding $T_{1/2}$=3(2) ps, at the edge of the sensitivity of the experimental method. This first result for the $11/2^+_1$ state half-life in neutron-rich Sb isotopes provides a quadrupole reduced transition probability to the ground state of B(E2)=$1.4^{+1.5}_{-0.6}$ W.u., very close to the B(E2;$2^+_1 \rightarrow 0^+_1$) in ^{130}Sn. Realistic shell-model calculations reproduce well both the experimental level scheme of ^{131}Sb and the B(E2;$11/2^+_1 \rightarrow 7/2^+_1$) value, indicting a dominant $2^+(^{130}\text{Sn}) \otimes \pi g_{7/2}$, core-proton coupled configuration for the $11/2^+_1$ state.

1. Introduction

The energies of the $11/2^+_1$ states in neutron-rich Sb isotopes are almost the same of the 2^+ states in the underlying Sn nuclei [1]. This may suggest that the $11/2^+_1$ state could be interpreted in terms of core-proton coupling. In this scheme, one assumes that the low-lying spectrum of the odd-even system can be well described by coupling the odd nucleon in the lowest allowed orbital to the ground and the 2^+ states of the neighboring even-even core. Particle- and hole-core coupled states around closed shells are of particular interest for nuclear structure, as reported, for example, in Refs. [2] and [3], for Ca isotopes and the ^{133}Sb nucleus, respectively. In the so-called weak coupling limit, the extra particle does not perturb the core and the total quadrupole strength of the multiplet obtained from the 2^+_1 state is conserved [4]. This simple description can

†Present address: Center for Exotic Nuclear Studies, Inst. for Basic Science, Daejeon 34126, Rep. of Korea

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

break down when particle-core correlations provide extra strength owing to the proton-neutron interaction. In this work, the structure of the $11/2_1^+$ state in ^{131}Sb was investigated by lifetime measurements using γ-ray spectroscopy techniques to probe its $2^+(^{130}\mathrm{Sn}) \otimes \pi g_{7/2}$ core-proton coupled nature. The results are compared with realistic shell-model calculations performed in a large valance space.

2. The experiment

The experiment was performed at Insititut Laue-Langevin (ILL) with the LOHENGRIN spectrometer [5]. The nuclei of interest were produced by thermal neutron-induced fission of a ^{235}U target. Fission fragments were selected with magnetic and electric fields, according to their A/q and E/q, mass-to-charge and energy-to-charge ratios, respectively. Finally, ions were collimated by a refocusing magnet [6] to the focal plane of the spectrometer, where their γ decay was measured by two HPGe clover detectors and four $LaBr_3$(Ce) scintillators. Considering a time of flight of about 2 μs, only the γ decay from isomeric states can be detected.

In ^{131}Sb, three isomers are known, namely the $(23/2^+)$, $(19/2^-)$, and $(15/2^-)$ states at 2165.6 keV, 1687.2 keV, and 1676.1 keV, with half-lives of 0.97(3), 4.3(8) and 64(3) μs, respectively [7, 1]. The $11/2_1^+$ state in ^{131}Sb is fed by the 450-keV transition depopulating the 64-μs isomer and decays to the ground state via a stretched E2 transition of 1126 keV, as shown in the left panel of Fig. 1. In the same picture, the level and decay scheme of ^{131}Sb measured in this experiment is displayed. The 450-1226-keV coincident spectrum is presented on the right panel of Fig. 1 for both HPGe and $LaBr_3$(Ce) detectors, showing the selectivity achieved in the present experiment. The lifetime of the $11/2_1^+$ state was measured by using the *generalized centroid difference* (GCD) method [8], applied to the 450-1226-keV, feeding-decay (E_f,E_d) cascade. The background contribution was evaluated with the method introduced in Ref. [9] and already used in Refs. [10, 11, 12]. The lifetime value was obtained by $2\tau = \Delta$C-PRD(E_f,E_d), where ΔC is the centroid difference between the delayed (D) and antidelayed (AD) time distributions. The PRD(E_f,E_d) correction is the so-called *prompt response difference*, which takes into account time-walk effects in $LaBr_3$(Ce) detectors [8].

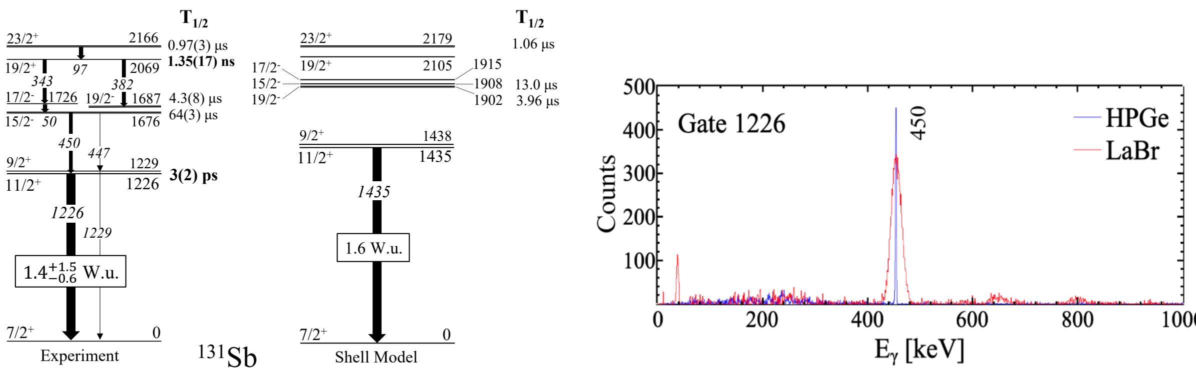

Figure 1. (Left) Experimental level and decay scheme of ^{131}Sb observed in the present experiment compared to shell-model calculations. Half lives measured in this work are highlighted in bold. The obtained B(E2;$11/2_1^+ \rightarrow 7/2_1^+$) value is also reported. (Right) Background-subtracted projected spectrum showing a clean coincidence between the 450-keV and 1226-keV γ rays, for both HPGe and $LaBr_3$(Ce) detectors.

The result for the lifetime of the $11/2_1^+$ state is τ=5(3) ps, which corresponds to $T_{1/2}$=3(2) ps, at the limit of the sensitivity of the experimental method. Also the lifetime of the $19/2^+$ state at 2069 keV was measured in this work using the decay slope method, with gates applied on both the $19/2^+ \rightarrow 17/2^-$ and $19/2^+ \rightarrow 19/2^-$ decaying transitions. The weighted average lifetime obtained from the separate analysis of the D and AD time distributions is $\tau = 1944(246)$ ps, corresponding to $T_{1/2}$=1347(171) ps. These results are reported in the left panel of Fig. 1.

3. Discussion

The measured lifetime of the $11/2^+$ state in ^{131}Sb enabled to assess the electric-quadrupole reduced transition probability to the ground state, providing B(E2;$11/2^+_1 \rightarrow 7/2^+_1$)=$1.4^{+1.5}_{-0.6}$ W.u., indicating a non-collective nature of this state. This result is very close to the measured B(E2;$2^+_1 \rightarrow 0^+_1$)=1.18(26) W.u of the ^{130}Sn nucleus [13], suggesting that the extra proton does not perturb the Sn core. As a matter of fact, the $11/2^+$ state is expected to be a member of the $2^+(^{130}\mathrm{Sn}) \otimes \pi g_{7/2}$ multiplet, corresponding to the maximum spin alignment.
Experimental data are compared with realistic shell-model calculations performed with the KSHELL code [14]. An inert ^{100}Sn core was considered, with a valence space composed by the $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$ and $0h_{11/2}$ orbitals for both protons and neutrons. In this framework, the two-body effective interaction was derived with many-body perturbation theory from the CD-Bonn nucleon-nucleon potential [15] renormalized by way of the $V_{\mathrm{low-k}}$ approach [16] with the addition of the Coulomb potential. The $\hat{Q}$ - box folded-diagram approach [17] was adopted, including one and two-body diagrams up to the third order. Effective charges are chosen to be $e_p = 1.7e$ and $e_n = 0.67e$, in order to reproduce the experimental B(E2; $2^+_1 \rightarrow 0^+_1$) = 31.5(1.0) and 1.18(26) W.u. of ^{134}Te and ^{130}Sn, respectively. The calculated energies and wave-function components of low-lying state in ^{131}Sb are shown in Tab. 1.

Table 1. Calculated energies and wave-function structure of low-lying states in ^{131}Sb in terms of ^{130}Sn $\otimes$ π(lj). Only components ≥ 0.02 are reported.

j^π	E [MeV]	$0^+_1 \otimes g_{7/2}$	$2^+_1 \otimes g_{7/2}$	$2^+_2 \otimes g_{7/2}$	$4^+_1 \otimes g_{7/2}$	$0^+_1 \otimes d_{3/2}$	$0^+_1 \otimes d_{5/2}$	$2^+_1 \otimes d_{5/2}$
$\mathbf{7/2^+_1}$	0.0	0.91	0.06	-	-	-	-	-
$\mathbf{5/2^+_1}$	0.942	-	0.03	-	-	-	0.90	0.03
$\mathbf{5/2^+_2}$	1.359	-	0.91	-	-	-	0.02	0.02
$\mathbf{3/2^+_1}$	1.381	0.79	-	-	0.20	-	-	-
$\mathbf{11/2^+_1}$	1.435	-	0.88	-	0.08	-	-	-
$\mathbf{9/2^+_1}$	1.438	-	0.73	-	0.13	-	-	-
$\mathbf{7/2^+_2}$	1.696	0.03	0.55	0.11	0.24	-	-	-

First of all, we note that a good agreement is found in terms of spin-parity sequences and energies, compared to the experimental level scheme shown in Fig. 1. The theoretical level scheme of ^{131}Sb is also shown in Fig. 1. Moreover, the calculated wave function of the $11/2^+_1$ state is dominated by the $2^+(^{130}\mathrm{Sn}) \otimes \pi g_{7/2}$ configuration (88%) and the predicted B(E2;$11/2^+_1 \rightarrow 7/2^+_1$)=1.6 W.u. results to be in perfect agreement with the experimental value of $1.4^{+1.5}_{-0.6}$ W.u. obtained in this work. Overall, both the experimental result and realistic shell-model calculations point to a good description of the $11/2^+_1$ state in ^{131}Sb in terms of proton-core coupling.
It interesting to compare this finding with the results for the neighbouring ^{129}Sb nucleus [18]. In this case, a larger fragmentation of the wave function is predicted, with a 78% coming from the $2^+(^{128}\mathrm{Sn}) \otimes \pi g_{7/2}$ coupling. On top of this, a B(E2;$11/2^+_1 \rightarrow 7/2^+_1$) value of 7.5(5) W.u. is reported, which exceeds the B(E2;$2^+_1 \rightarrow 0^+_1$)=4.2(3) W.u of the ^{128}Sn core [19]. This enhancement is partially predicted by shell-model calculations, with a calculated B(E2;$11/2^+_1 \rightarrow 7/2^+_1$) of 5.1 W.u. which can be ascribed to a constructive interference of the

proton-neutron term in the quadrupole strength. In the case of ^{131}Sb, the latter is found to be smaller and of the same order of magnitude of the proton term. Finally, we note that also the $15/2^+_1$ states in both ^{131}Sb and ^{129}Sb were calculated within the same shell-model framework. Their wave functions were found to be dominated by the $4^+(^{A}\mathrm{Sn}) \otimes \pi g_{7/2}$ component (85% and 80%, respectively), indicating that the core-proton coupling scheme can be extended also to higher-spin states along the Sb isotopic chain.

4. Conclusions

In conclusion, the lifetime of the $11/2^+$ state in ^{131}Sb was measured at the LOHENGRIN spectrometer of Insititut Laue-Langevin, using neutron-induced fission of ^{235}U and the fast timing technique. A half-life of 3(2) ps was found, at the edge of the experimental method, which corresponds to a $B(E2;11/2^+_1 \rightarrow 7/2^+_1)=1.4^{+1.5}_{-0.6}$ W.u. for its stretched E2 decay. This result, along with the known $B(E2;2^+_1 \rightarrow 0^+_1)$ value in ^{130}Sn and realistic shell model calculations, indicate an almost pure core-proton coupled structure for this state, dominated by the $2^+(^{130}\mathrm{Sn}) \otimes \pi g_{7/2}$ configuration.

Acknowledgments

This work was supported in part by the Italian Istituto Nazionale di Fisica Nucleare, the Polish National Science Centre, Poland, under research project No. 2020/39/D/ST2/03510, the Polish National Agency for Academic Exchange (NAWA) within the Bekker programme under grant PPN/BEK/2020/1/00431/U/00001, the Institute for Basic Science (IBS-R031-D1), the German DFG under grant JO391/18-1, and the Fonds de la Recherche Scientifique - FNRS under grants numbers J.0174.22 and 4.45.10.08.

References

[1] Biswas S, Lemasson A, Rejmund M, Navin A, Kim Y H, Michelagnoli C, Stefan I, Banik R, Bednarczyk P, Bhattacharya S, Bhattacharyya S, Clément E, Crawford H L, de France G, Fallon P, Frémont G, Goupil J, Jacquot B, Li H J, Ljungvall J *et al.* 2019 *Phys. Rev. C* **99**(6) 064302 URL `https://link.aps.org/doi/10.1103/PhysRevC.99.064302`

[2] Bocchi G, Leoni S, Fornal B, Colò G, Bortignon P, Bottoni S, Bracco A, Michelagnoli C, Bazzacco D, Blanc A, de France G, Jentschel M, Köster U, Mutti P, Régis J M, Simpson G, Soldner T, Ur C, Urban W, Fraile L, Lozeva R, Belvito B, Benzoni G, Bruce A, Carroll R, Cieplicka-Oryczak N, Crespi F, Didierjean F, Jolie J, Korten W, Kröll T, Lalkovski S, Mach H, Mărginean N, Melon B, Mengoni D, Million B, Nannini A, Napoli D, Olaizola B, Paziy V, Podolyák Z, Regan P, Saed-Samii N, Szpak B and Vedia V 2016 *Physics Letters B* **760** 273–278 ISSN 0370-2693 URL `https://www.sciencedirect.com/science/article/pii/S0370269316303252`

[3] Bottoni S, Cieplicka-Oryńczak N, Leoni S, Fornal B, Colò G, Bortignon P F, Bocchi G, Bazzacco D, Benzoni G, Blanc A, Bracco A, Ceruti S, Crespi F C L, de France G, Gamba E R, Iskra L W, Jentschel M, Köster U, Michelagnoli C, Million B, Mengoni D, Mutti P, Niu Y, Porzio C, Simpson G, Soldner T, Szpak B, Türler A, Ur C A and Urban W 2021 *Phys. Rev. C* **103**(1) 014320

[4] de Shalit A 1961 *Phys. Rev.* **122**(5) 1530–1536 URL `https://link.aps.org/doi/10.1103/PhysRev.122.1530`

[5] Armbruster P, Asghar M, Bocquet J, Decker R, Ewald H, Greif J, Moll E, Pfeiffer B, Schrader H, Schussler F, Siegert G and Wollnik H 1976 *Nucl. Instrum. Methods* **139** 213 – 222 ISSN 0029-554X URL `http://www.sciencedirect.com/science/article/pii/0029554X76906777`

[6] Fioni G, Faust H, Gross M, Hesse M, Armbruster P, Gönnenwein F and Münzenberg G 1993 *Nucl. Instrum. Methods Phys. Res., Sect. A* **332** 175 – 180 ISSN 0168-9002 URL `http://www.sciencedirect.com/science/article/pii/0168900293907568`

[7] Genevey J, Pinston J A, Faust H, Foin C, Oberstedt S and Rejmund M 2000 *Eur. Phys. J. A* **9** 191–195 URL `https://doi.org/10.1007/s100500070036`

[8] Régis J M, Mach H, Simpson G, Jolie J, Pascovici G, Saed-Samii N, Warr N, Bruce A, Degenkolb J, Fraile L, Fransen C, Ghita D, Kisyov S, Koester U, Korgul A, Lalkovski S, Mărginean N, Mutti P, Olaizola B, Podolyák Z *et al.* 2013 *Nucl. Instrum. Methods Phys. Res., Sect. A* **726** 191 – 202 ISSN 0168-9002 URL `http://www.sciencedirect.com/science/article/pii/S0168900213007377`

[9] Gamba E, Bruce A and Rudigier M 2019 *Nucl. Instrum. Methods Phys. Res., Sect. A* **928** 93 – 103 ISSN 0168-9002 URL http://www.sciencedirect.com/science/article/pii/S0168900219303365

[10] Gamba E R, Bruce A M, Lalkovski S, Rudigier M, Bottoni S, Carpenter M P, Zhu S, Anderson J T, Ayangeakaa A D, Berry T A, Burrows I, Gallardo M C, Carroll R J, Copp P, Cullen D M, Daniel T, Martínez G F, Greene J P, Gurgi L A *et al.* 2019 *Phys. Rev. C* **100**(4) 044309 URL https://link.aps.org/doi/10.1103/PhysRevC.100.044309

[11] Rudigier M, Walker P, Canavan R, Podolyák Z, Regan P, Söderström P A, Lebois M, Wilson J, Jovancevic N, Blazhev A, Benito J, Bottoni S, Brunet M, Cieplicka-Oryńczak N, Courtin S, Doherty D, Fraile L, Hadyńska-Klek K, Heine M, Iskra L *et al.* 2020 *Phys. Lett. B* **801** 135140 ISSN 0370-2693 URL http://www.sciencedirect.com/science/article/pii/S0370269319308627

[12] Canavan R L, Rudigier M, Regan P H, Lebois M, Wilson J N, Jovancevic N, Söderström P A, Collins S M, Thisse D, Benito J, Bottoni S, Brunet M, Cieplicka-Oryńczak N, Courtin S, Doherty D T, Fraile L M, Hadyńska-Klek K, Häfner G, Heine M, Iskra L W *et al.* 2020 *Phys. Rev. C* **101**(2) 024313 URL https://link.aps.org/doi/10.1103/PhysRevC.101.024313

[13] Pritychenko B, Běták E, Kellett M, Singh B and Totans J 2011 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **640** 213–218 ISSN 0168-9002 URL https://www.sciencedirect.com/science/article/pii/S0168900211005584

[14] Shimizu N, Mizusaki T, Utsuno Y and Tsunoda Y 2019 *Computer Physics Communications* **244** 372–384 ISSN 0010-4655 URL https://www.sciencedirect.com/science/article/pii/S0010465519301985

[15] Machleidt R 2001 *Phys. Rev. C* **63**(2) 024001 URL https://link.aps.org/doi/10.1103/PhysRevC.63.024001

[16] Bonger S, Kuo T and Coraggio L 2001 *Nuclear Physics A* **684** 432–436 ISSN 0375-9474 few-Body Problems in Physics URL https://www.sciencedirect.com/science/article/pii/S0375947401004493

[17] Coraggio L, Covello A, Gargano A, Itaco N and Kuo T 2012 *Annals of Physics* **327** 2125–2151 ISSN 0003-4916 URL https://www.sciencedirect.com/science/article/pii/S0003491612000681

[18] Gray T J, Allmond J M, Stuchbery A E, Yu C H, Baktash C, Gargano A, Galindo-Uribarri A, Radford D C, Batchelder J C, Beene J R, Bingham C R, Coraggio L, Covello A, Danchev M, Gross C J, Hausladen P A, Itaco N, Krolas W, Liang J F, Padilla-Rodal E, Pavan J, Stracener D W and Varner R L 2020 *Phys. Rev. Lett.* **124**(3) 032502 URL https://link.aps.org/doi/10.1103/PhysRevLett.124.032502

[19] Allmond J M, Radford D C, Baktash C, Batchelder J C, Galindo-Uribarri A, Gross C J, Hausladen P A, Lagergren K, Larochelle Y, Padilla-Rodal E and Yu C H 2011 *Phys. Rev. C* **84**(6) 061303 URL https://link.aps.org/doi/10.1103/PhysRevC.84.061303