

Letter of clarification to the ISOLDE and Neutron
Time-of-Flight Experiments Committee related to
INTC-2016-054, P-484

Nuclear quadrupole moments and charge radii of the $_{51}\text{Sb}$
isotopes via collinear laser spectroscopy

January 12, 2017

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1 Introduction

The original proposal was defended at the 54th meeting of the INTC held on November 4th, 2016, to study the nuclear quadrupole moments and charge radii of the antimony isotopes using collinear laser spectroscopy (COLLAPS). The purpose of this letter of clarification is to address the comments/issues raised by the INTC:

The INTC asks for a letter of clarification to address the physics motivation in more detail. In particular, the authors should address the preliminary results for the recently obtained Sn isotopic chain, the knowledge about the structure of the Sb isotopes from other techniques, and theoretical models that may help to interpret the data that will be obtained.

2 Physics motivation

Because of the single proton outside the $Z = 50$ shell closure, antimony isotopes provide an unique opportunity to probe the proton single-particle orbits beyond $Z = 50$, and thus to address the evolution of proton single-particle orbits as a function of neutron number. At the same time, collectivity due to the core excitation can play an important role in the low-lying states of Sb isotopes. This makes the Sb isotopes an ideal testing ground for various theoretical models to understand the interplay between single-particle and collective effects far away from the stability line.

Along this direction, many efforts have been devoted to obtain experimental nuclear-structure information in Sb isotopes comprehensively. The studies include extracting spectroscopic factors from nucleon transfer reactions [1, 2], measuring γ rays and transition probabilities via fission/fusion reactions or decay spectroscopy [3–5], and nuclear electromagnetic-moment measurements through various techniques [6–8].

2.1 Knowledge from spectroscopic studies

Since the spin-orbit splitting in heavier nuclei is responsible for the “magic numbers” of closed shells, it is of great significance to verify the single-particle character of the low-lying states in exotic Sb isotopes, which is essential for the evaluation of proton spin-orbit splitting strengths far from the β -stability line [2]. Conjeaud *et al.* identified the first $11/2^-$ states in $^{113-125}\text{Sb}$ from the one-proton transfer reaction ($^3\text{He}, d$), with a spectroscopic factor ~ 0.5 [1]. This result was in agreement with a later measurement using the (α, t) reaction at 80 MeV, which gave the spectroscopic factors 0.64 and 0.42 for the $7/2_1^+$ and $11/2_1^-$ states in ^{117}Sb respectively [9]. These results indicated that the investigated $11/2^-$ states are not of pure single-particle configuration. However, the conclusion was at variance with a more recent set of experimental data obtained by Schiffer *et al.* using the $\text{Sn}(\alpha, t)\text{Sb}$ transfer reactions [2], in which the spectroscopic factors of the $7/2_1^+$ and $11/2_1^-$ states were found to be close to unity for $^{113-125}\text{Sb}$. The latter results clearly suggest that the origins of the two low-lying states in Sb isotopes are $\pi g_{7/2}$ and $\pi h_{11/2}$ beyond $Z = 50$, respectively. The discrepancy between the old and new experimental data

requires additional experimental studies that underline the microscopic properties of the states of interest. Theoretically, on the other hand, the shell model calculation using the full $1d_{5/2}-0g_{7/2}-0h_{11/2}-2s_{1/2}-1d_{3/2}$ space upon tin cores supports the former spectroscopic factors, suggesting that the low-lying states $5/2^+$, $7/2^+$, and $11/2^-$ in $^{113-125}\text{Sb}$ show configuration mixing to a certain extent [10].

Besides nucleon-transfer reactions, a more complete set of low-lying states in Sb isotopes, in particular the ones far from stable isotopes, was populated and studied via fusion/fission reactions or decay spectroscopy. Transition probabilities of several low-lying states were also deduced from their measurable decay half lives (*e.g.* the $B(E3)$ value of the $11/2^-$ state in ^{133}Sb [11]). The properties of the low-lying levels of the odd- A Sb isotopes are reproduced well in theoretical calculations that take into account an odd proton in the spherical orbitals of the $Z = 50 - 82$ major shell coupled to the quadrupole (2^+) and octupole (3^-) phonon excitation of the $Z = 50$ Sn core (*e.g.* ^{133}Sb in Ref. [5]), indicating that the excitation of the even-even tin core plays an important role in the low-lying states of Sb isotopes.

2.2 Nuclear electromagnetic moments

To understand the ground-state microscopic configuration of the odd- A Sb isotopes, magnetic and quadrupole moments were extracted via various approaches. An overview is presented in Table 1. For magnetic moments, the g factors of the $5/2_1^+$ states were known from $N = 64$ to $N = 70$, whereas the g factors of the $7/2_1^+$ states were measured from $N = 70$ onwards, till the neutron shell closure $N = 82$. The data is plotted in Fig. 1. It can be noticed that the measured g factors (for both $5/2_1^+$ and $7/2_1^+$) strongly deviate from the single-particle Schmidt values. Even at the neutron closed shell $N = 82$, a quenching factor 0.7 to the proton spin g factor can merely reduce part of the discrepancy (see Fig. 1). By taking into account the contribution from the core-polarization effects as well as the meson-exchange currents, effective g factors $g_{l,\pi} = 1.138$ and $g_{s,\pi} = 0.651 \times g_{s,\pi}^{(\text{free})}$ were deduced, to reproduce the $g(7/2_1^+)$ factors of $^{121-133}\text{Sb}$ using a simple proton-core coupling model [8]. A more complex shell model calculation using the full $1d_{5/2}-0g_{7/2}-0h_{11/2}-2s_{1/2}-1d_{3/2}$ space for both valence proton and neutrons was carried out for $^{121-133}\text{Sb}$ [16]. The effective interactions were the same as that employed in Ref. [10]. In Fig. 1, the calculated g factors for the $7/2_1^+$ states, with effective proton/neutron g factors taken as $g_{l,\pi} = 1.1$, $g_{l,\nu} = -0.1$, and $g_s = 0.6 \times g_s^{(\text{free})}$, are presented in red line, which nicely reproduces the experimental data at $N = 70 - 82$. The deviation between experimental data and Schmidt value at $N = 82$, which is partly due to the $M1$ excitation between the proton spin-orbit partners $g_{9/2}$ and $g_{7/2}$ across $Z = 50$, was corrected via introducing the effective g factors, while the variation of g factors in less exotic Sb nuclei was due to the increasing neutron collectivity within the major shell. However, it is noted that the magnetic moment in heavy or medium-heavy nuclei is not very sensitive to coupling of valence particles to quadrupole vibrations ($E2$) of the core [17]. In order to address the evolution of core collectivity towards $N = 82$, and possible neutron excitation across the major shell (*e.g.* the $E2$ excitation from $\nu h_{11/2}$ to $\nu f_{7/2}$), it is necessary to investigate the quadrupole moments of neutron-rich Sb isotopes.

Compared with magnetic moments, the experimental data for quadrupole moments is

Table 1: Literature of the Sb isotopes relevant to the proposal. The spin in parenthesis means the value is obtained from indirect measurement such as β -decay experiments or from systematic extrapolation. The data of spin and half life is taken from Ref. [12]. The data of electromagnetic moments is taken from Ref. [13–15]. The abbreviation of methods is listed as follows. NO/S: Static (low-temperature) nuclear orientation; AB: Atomic beam magnetic resonance; NMR/ON: Nuclear magnetic resonance on oriented nuclei; NMR: Nuclear magnetic resonance; NO/D: Dynamic nuclear orientation.

Nuclide	I^π	$T_{1/2}$	Magnetic moment		Quadrupole moment	
			μ (μ_N)	method	Q (barn)	method
^{112}Sb	(3 ⁺)	53.5(6) s				
^{113}Sb	5/2 ⁺	6.67(7) min				
^{114}Sb	3 ⁺	3.49(3) min	1.72(8)	NO/S		
^{115}Sb	5/2 ⁺	32.1(3) min	+3.46(1)	AB	-0.36(6)	AB
^{116}Sb	3 ⁺	15.8(8) min	2.715(9)	NMR/ON		
^{117}Sb	5/2 ⁺	2.80(1) h	+3.43(6)	AB	0.2(12)	AB
^{118}Sb	1 ⁺	3.6(1) min	2.47(7)	AB		
	8 ⁻	5.00(2) h	2.32(4)	NMR/ON		
^{119}Sb	5/2 ⁺	38.19(22) h	+3.45(1)	AB	-0.37(6)	AB
^{120}Sb	1 ⁺	15.89(4) min	2.3(2)	AB		
	8 ⁻	5.76(2) d	2.34(1)	NMR/ON		
^{121}Sb	5/2 ⁺	stable	+3.3634(3)	NMR	-0.543(11)	O
^{122}Sb	2 ⁻	2.7238(2) d	-1.90(2)	NO/D	+1.28(8)	O
^{123}Sb	7/2 ⁺	stable	+2.5498(2)	NMR	-0.692(14)	O
^{124}Sb	3 ⁻	60.20(3) d	1.20(2)	NMR/ON	+2.8(2)	NO/S
	5 ⁺	93(5) s				
	(8) ⁻	20.2(2) min				
^{125}Sb	7/2 ⁺	2.75856(25) y	+2.63(4)	NMR		
^{126}Sb	(8) ⁻	12.35(6) d	1.28(7)	NO/S		
	(5) ⁺	19.15(8) min				
	(3) ⁻	about 11 s				
^{127}Sb	7/2 ⁺	3.85(5) d	2.697(6)	NMR/ON		
^{128}Sb	8 ⁻	9.05(4) h	1.3(2)	NO/S		
	5 ⁺					
^{129}Sb	7/2 ⁺	4.366(26) h	2.79(2)	NMR/ON		
	(19/2) ⁻	17.7(1) min				
^{130}Sb	(8) ⁻	39.5(8) min				
	(4,5) ⁺	6.3(2) min				
^{131}Sb	(7/2) ⁺	23.03(4) min	2.89(1)	NMR/ON		
^{132}Sb	(4) ⁺	2.79(7) min				
	(8) ⁻	4.10(5) min				
^{133}Sb	(7/2) ⁺	2.34(5) min	3.00(1)	NMR/ON		
^{134}Sb	(0) ⁻	0.78(6) s				
	(7) ⁻	10.07(5) s				
^{135}Sb	(7/2) ⁺	1.679(15) s				

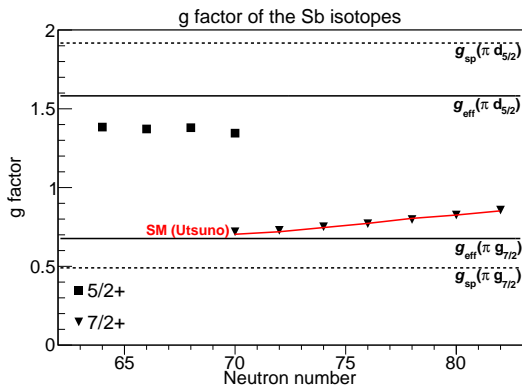


Figure 1: The experimental g factors of the $5/2_1^+$ and $7/2_1^+$ states of the odd- A Sb isotopes with $N = 64 - 82$. All the experimental values are taken from Ref. [13]. For comparison, the single-particle (s.p.) Schmidt values g_{sp} (with $g_{s,\pi}^{(free)} = 5.587$ and $g_{l,\pi}^{(free)} = 1$) and effective s.p. values g_{eff} (with $g_{s,\pi} = 0.7 \times g_{s,\pi}^{(free)}$ and $g_{l,\pi}^{(free)}$) are drawn for the proton $d_{5/2}$ and $g_{7/2}$ s.p. orbits. The shell model calculation (by Utsuno *et al.*) on the $7/2_1^+$ states is also presented [16]. See text for details.

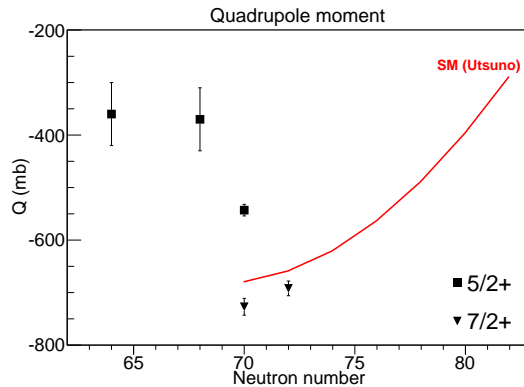


Figure 2: The g.s. quadrupole moments of the odd-even Sb isotopes with $N = 64 - 72$. The data of ^{117}Sb (0.2 ± 1.2 barn [14]) is not plotted on the figure because of its unknown sign and large uncertainty. All the experimental values are taken from Ref. [14, 15]. The shell model calculation (by Utsuno *et al.*) on the $7/2_1^+$ quadrupole moment is also presented [16]. See text for details.

much more scarce in the Sb isotopic chain. As shown in Fig. 2, only a few Q moments are available for odd- A Sb isotopes up to $N = 72$. The same shell model calculation [16] was employed to predict the Q moments of the $7/2_1^+$ ground state in Sb isotopes till $N = 82$. With effective charges taken as $(e_\pi, e_\nu) = (1.5e, 1.0e)$, whose neutron part was determined to reproduce the $B(E2)$ data in Sn isotopes, the calculated Q moments are plotted in Fig. 2. The limited experimental data at $N = 70, 72$ fits fairly well to the calculation. Since the model space only consists of one proton and neutron major shell, the calculation predicts a smooth decreasing trend (in magnitude) towards $N = 82$, which is reasonable if $N = 82$ is a good shell closure. Hence, the unknown Q moments in more neutron-rich Sb isotopes can serve as a stringent test for the neutron excitation across $N = 82$, by examining if the new experimental data follows the systematic trend predicted by the “simple” shell model calculation without considering neutron core excitation. If a sizable deviation between experimental data and theory was observed in more neutron-rich nuclei, core excitation across the $N = 82$ gap can be expected to a certain extent. It is interesting to note that recently the Monte-Carlo shell model calculation developed by the University of Tokyo group can diagonalize the Hamiltonian in the neutron space including all the orbits in the major shell $50 - 82$, plus $0g_{9/2}$ below $N = 50$ and $1f_{7/2}, 2p_{3/2}$ above $N = 82$ [18]. With the new calculation and the Q moments going to be measured, it is possible to discuss quantitatively the amount of contribution in the ground states of neutron-rich Sb isotopes from orbits in different major shells.

In addition to the comparison with complex nuclear models, the systematics of quadrupole

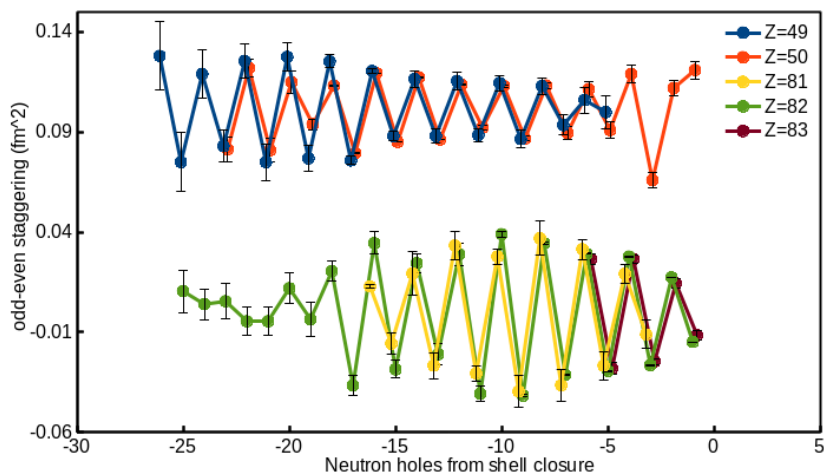


Figure 3: The odd-even staggering of $\delta\langle r^2 \rangle$ along the In ($Z = 49$), Sn ($Z = 50$), Tl ($Z = 81$), Pb ($Z = 82$), and Bi ($Z = 83$) isotopic chains as a function of neutron excess (negative for hole) of the $N = 82$ and $N = 126$ closed shells, respectively. See text for details.

moments itself can display remarkable feature. Preliminary analysis of the IS573 experiment shows that a number of quadrupole moments of Sn isotopes in the literature deviate from the values determined from our data. Our observations on the $11/2^-$ states, in particular, are now consistent with the corresponding trend in the Cd isotopes [19], two protons below Sn. Furthermore, these quadrupole moments of Sn appear to be related to an isomer shift following a parabolic trend with a minimum in the middle of the $h_{11/2}$ shell, an effect so far observed only in the Cd species [20]. These findings on Sn isotopes are, however, preliminary, until they are supplemented by a measurement in another atomic transition.

In Sb isotopes, the transition of choice offers excellent sensitivity to the nuclear parameters while physics-wise Sb is one step higher in complexity with respect to Cd and Sn, since it has an odd proton on top of the closed $Z = 50$ shell. Surely such proton configuration will manifest itself in some distinct way in the proposed measurements. Hence, starting from the “simple structure” rooted in the Cd nuclei, and possibly also in their Sn counterparts, the Sb isotopes will bring a different picture of simplicity, or alternatively of its disappearance.

2.3 Nuclear charge radii

The nuclear charge radius is one of the most effective probes to investigate the evolution of nuclear structure. As discussed in the original proposal, the systematics of nuclear charge radii along an isotopic chain usually shows different slopes before and after a major shell gap, giving rise to a kink at neutron magic numbers. According to existing experimental data, the slope of the kink depends on proton numbers, of which the underlying mechanics has not been well understood. The new charge-radius data measured for Sb isotopes will provide a good complement to the theoretical study of the kink at neutron closed shells. Besides, the odd-even staggering of mean-square charge radius change $\delta\langle r^2 \rangle$ also shows

characteristic behaviors at neutron closed shells. Here, the staggering parameter in each isotopic chain is defined as

$$S_{\text{odd-even}}(Z, N) = \delta\langle r^2 \rangle_{Z,N} - \frac{1}{2} \left(\delta\langle r^2 \rangle_{Z,N-1} + \delta\langle r^2 \rangle_{Z,N+1} \right). \quad (1)$$

With all the experimental data taken from Ref. [21], the parameters are plotted against neutron excess of magic numbers (82 and 126) in Fig. 3. For a better view of the systematics, different vertical offsets are applied to the $N = 82$ (0.1 for In and Sn) and $N = 126$ (0 for Tl, Pb, and Bi) regions respectively. One can see from the figure that the odd- Z isotopic chains follow remarkably similar trends as that of their neighboring even- Z isotopic chain. Furthermore, in Tl, Pb, and Bi isotopes, the magnitude of the odd-even staggering gradually decreases when neutrons are approaching the magic number ($N = 126$), which is also the case in Sn and In isotopes till $N = 77$. From $N = 77$ onwards, however, the Sn isotopes show an abnormally strong staggering towards $N = 82$, while no data in In isotopes is available for comparison. Considering the great experimental difficulty to produce In isotopes near $N = 82$, it is of great interest to look at the charge radii in neutron-rich Sb isotopes, to verify whether the abnormal staggering is unique in Sn isotopes, or is an universal behavior at $N = 82$. The results may provide insight to the variation of neutron pairing interactions in neutron-rich nuclei. It is also noteworthy that many new bismuth charge radii have been measured at Gatchina and recently at ISOLDE/RILIS but not published yet [22]. The new results show significant differences between $Z = 82 \pm 1$ (for instance ^{188}Bi at $N = 105$ is strongly deformed like the light odd Hg isotopes, but ^{186}Tl is not). Along this direction, the Sb measurements will be able to provide the same comparisons for $Z = 49, 50$ and 51 .

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