EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Clarification to the ISOLDE and Neutron Time-of-Flight Committee

P-657: Collinear resonance ionization spectroscopy of neutron-deficient antimony isotopes, towards the proton drip line

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Abstract: This letter of clarification addresses the issues raised at the 72nd meeting of the INTC regarding proposal P-657. This proposal aims to measure the hyperfine structure of the neutron-deficient Sb (Z=51) isotopes with collinear resonance ionization spectroscopy in order to test our understanding of the effect of the valence proton on the nuclear structure around the Z=50 shell closure.

Requested shifts: 19 shifts with protons (+3 shifts without protons for setup)

1 Clarifications requested by the INTC

The authors would firstly like to express their thanks to the INTC for their consideration of this proposal. For clarity of presentation, the comments made by the INTC are copied below and addressed in the following sections:

1. Although the proposal is scientifically well motivated, it left many open questions that need to be clarified before the proposal can be approved. The proposal aims to compare the measured nuclear observables to theoretical predictions from density functional theory and ab-initio methods. However, there are no theory collaborators listed and the description of the theoretical models in this specific region, one proton above the closed Z=50 shell, is missing. Continuum effects and core breaking are mentioned specifically in the proposal. It should be better described which properties will be calculated to be compared with the experimental results, which theoretical framework will be used and how the theoretical calculations will be performed for the listed antimony isotopes.

2. The information on the current status of the spins of the proposed isotopes was missing. Most of them are tentative or based on systematics for $^{105-111}$Sb but only for ^{110}Sb was the spin mentioned as a new property to be determined.

3. Electromagnetic moments for ^{113}Sb have not been determined before but the proposal lists it as an already measured case.

1.1 Nuclear theory predictions

This proposal seeks to compare measurements of the magnetic moments, quadrupole moments and relative charge radii (from laser spectroscopy) to the predictions provided by three different theoretical frameworks: the Gamow Coupled Channel approach, Density Functional Theory and ab-initio Valence-Space IMSRG. Calculations will be provided by nuclear theory collaborators, who are included in the above author list in bold and have provided the theoretical input for this letter.

The pattern of low-lying states of the odd-A Sb isotopes is indicative of a weak quadrupole collectivity. This suggests that – in addition to the dominant $d_{5/2}$ component – a wave function component involving $s_{1/2}$ coupled to the 2^+ state of the Sn core is likely to be

present. The appearance of the s-wave contribution can give rise to halo-like behaviour for proton-bound Sb isotopes or enhanced proton emission for unbound isotopes. Investigating the impact of the proton separation energy and deformation on the charge radii and other properties can be carried out by means of the Gamow Coupled-Channel (GCC) framework [1]. The GCC method employs the Berggren ensemble technique to treat bound, scattering and Gamow states on the same footing. Similar to the case of ^{67}Kr [2], antimony isotopes can be modelled non-adiabatically in terms of a valence proton atop a vibrational core. By altering the strength of the proton-core interaction, charge radii can be calculated as a function of the proton separation energy and quadrupole coupling. By using the GCC method, we can identify the impact of continuum correlations on charge radii. The predictions (electromagnetic moments and charge radii) of this approach will provide a greater insight into the effect of the unbound proton states on the properties of the nucleus as the proton drip line at ^{105}Sb is approached, allowing investigation into the contribution of the unbound states to the nuclear deformation.

Density Functional Theory (DFT) can describe bulk properties of the nucleus (such as charge radii) across the nuclear chart, by assuming the nucleons move within their own self-consistently generated spin-dependent broken-symmetry-confining potential [3]. By using different energy density functionals, the influence of different variations (e.g. relativistic/spin-orbit corrections, time-odd components etc.) on the predicted properties (electromagnetic moments and charge radii) can be investigated. DFT/Hartree-Fock-Bogoliubov (HFB) calculations of charge radii along the Sb chain will be performed, using the recently-developed Fayans energy density functionals. These density functionals have been successfully applied to the neighbouring In (Z=49) isotopes that have been recently measured by CRIS, demonstrating the necessity of including time-odd terms in order to correctly reproduce their magnetic moments [4]. This approach can successfully compute the charge radii of proton-rich isotopes in the presence of low-lying particle continuum [5].

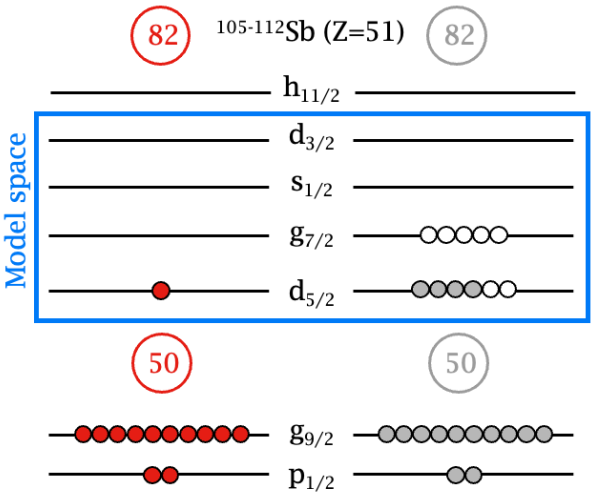

Figure 1: Occupation of nuclear orbitals for protons (red) and neutrons (grey) for the neutron-deficient Sb (Z=51) isotopes, from ^{105}Sb (N=54) (closed markers) to ^{112}Sb (N=61) (open markers). The blue box denotes the truncated model space to be used for VS-IMSRG calculations.

Valence-space in-medium similarity renormalization group (VS-IMSRG) calculations will provide predictions (electromagnetic moments and charge radii) using an ab-initio framework starting from 2- and 3-body nucleon-nucleon interactions derived from chiral effective field theory [6]. By truncating the proton and neutron valence space by removing the $h_{11/2}$ orbitals to reduce the dimension of the valence-space diagonalization (see Figure 1), calculation of the properties of the Sb isotopes is deemed feasible. While reproduction of the absolute charge radii is a known problem, calculations can provide insight into any nuclear structural changes reflected by relative charge radii. Recent advances have predicted properties of neighbouring In (Z=49) and Sn (Z=50) isotopes in order to compare with CRIS measurements, and are due to be published shortly [7, 8].

Calculations using the GCC method, DFT/HFB and ab-initio VS-IMSRG will provide predictions for the magnetic moments, quadrupole moments and charge radii of the neutron-deficient Sb isotopes. These predictions will be compared to our experimental results measured with laser spectroscopy. Comparison of the magnetic moments will allow investigation into the single-particle nature of the nuclear states, providing insight into the contribution of the different nuclear states to the nuclear wave function. Comparison of the quadrupole moments will provide insights into the evolution of static nuclear deformation as the proton drip line is approached. In addition, comparison of the charge radii will offer a complementary insight into the evolution of deformation, as the charge radii and associated odd-even-staggering parameter is highly-dependent on the nuclear shell structure as well as collective effects.

1.2 Nuclear spins

The spins of all proposed Sb isotopes, $^{105-111}$Sb, should have been included in the 'new results' column of Table 1. In the literature, the tentative spin assignments for the odd-A isotopes are based on systematics of the region, where the odd proton occupies the $d_{5/2}$ orbital. The spins for the odd-odd isotopes are also tentative and based on decay systematics. Studies with laser spectroscopy will provide unambiguous measurement of the nuclear spins of all proposed isotopes. For completeness, Table 1 is reproduced here.

Isotope	Half-life	Predicted yield ($/\mu$C)	Shifts requested	New results
^{123}Sb	Stable	3.0×10^{6}	3 (without protons)	-
$^{112-121}$Sb	>53.5 s	$>7.0\times10^{5}$	5	-
^{111}Sb	75 s	5.1×10^{5}	0.5	I, μ, Q_s, $\delta\langle r^2\rangle$
^{110}Sb	23 s	2.7×10^{4}	1	I, μ, Q_s, $\delta\langle r^2\rangle$
^{109}Sb	17 s	4.1×10^{3}	2	I, μ, Q_s, $\delta\langle r^2\rangle$
^{108}Sb	7.4 s	1.9×10^{2}	4	I, μ, Q_s, $\delta\langle r^2\rangle$
^{107}Sb	4.0 s	1.7×10^{1}	6	I, μ, Q_s, $\delta\langle r^2\rangle$
^{106,105}Sb	0.6 s, 1.22 s	1.3×10^{-1}	0.5	I, μ, Q_s, $\delta\langle r^2\rangle$

Table 1: Isotopes of interest, half-lives, predicted yields from a LaC target, number of shifts requested and potential new results. 3 shifts (without protons) are requested before the experiment for beam tuning, charge-exchange cell heating and laser/atom interaction optimization. 0.5 shifts are requested after the experiment for yield/background measurements of ^{106,105}Sb to guide future proposals.

1.3 Moments of ^{113}Sb

While the electromagnetic moments for ^{113}Sb have not been measured with any other method e.g. time-dependent perturbed angular correlation method, atomic beam magnetic resonance, nuclear magnetic resonance etc. (unlike the isotopes $^{112,114-131,133}$Sb), COLLAPS have recently measured the electromagnetic moments for ^{113}Sb with laser spectroscopy. While not yet published, the COLLAPS experiment studied $^{112-134}$Sb, and as such, ^{113}Sb was listed as 'measured' in this proposal.

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