EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status report to the ISOLDE and Neutron Time-of-Flight Committee

Status report for the COLLAPS collaboration

September 25, 2019

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CERN-INTC-2019-033 / INTC-SR-090
25/09/2019

Abstract: Two collinear laser spectroscopy experiments using the COLLAPS set-up have outstanding shifts remaining. In this status report, first a brief summary on the status of the experiments which were closed between long shutdown 1 and 2 is given. Then the physics relevance of the experiments with open shifts and the technical developments towards their successful completion are presented.

Remaining shifts: IS529 - 17 shifts, IS635 - 6 shifts

1 Introduction

At the COLLAPS beam line, collinear laser spectroscopy has been used to study the structure of radioactive isotopes for almost four decades now. By measuring atomic or ionic hyperfine spectra with high resolution, this technique gives access to spins, magnetic dipole moments, electric quadrupole moments and mean-square charge radii of nuclear ground states or long-lived isomers. Not only do these observables give valuable information on the nuclear structure of a state such as its single-particle nature or the degree of collectivity, the spin can often be measured unambiguously, providing a firm assignment essential for building reliable level schemes from other techniques. A detailed description of the COLLAPS set-up and technique can e.g. be found in [1] and references therein.

In this document, we will report on the status of the COLLAPS experiments performed between the first and the second long shutdown (LS1 and LS2) and we will elaborate on the experiments which have outstanding shifts remaining.

2 Summary of experiments without outstanding shifts

In the last years, the efforts of the COLLAPS collaboration have been mainly focussed on regions of the nuclear chart around three major proton shells ($Z = 20,\ 28,\ 50$). In these regions, isotopes are known to exhibit a relatively simple structure due to the few valence nucleons involved, making them ideal cases to benchmark state-of-the-art nuclear models and to investigate shell structure evolution far from stability. Apart from this core programme in the vicinity of magic numbers, occasionally isotopic chains with very specific physics questions were addressed. These include the Al isotopes, which gives insight in proton-neutron pairing and provide input for extracting V_{ud} from superallowed β-decays, and the Bi isotopes of which the hyperfine parameters are very sensitive to the hyperfine anomaly. Here we summarise the main results and publications of the COLLAPS experiments between LS1 and LS2. We consider all of these experiments closed and do not wish the keep remaining shifts, except for those discussed separately in section 3.

Table 1: Main COLLAPS results and publications obtained between long shutdown 1 and 2.

Experiment	Isotopes	Status	Results, publications and PhD theses
IS508	$^{51,53-64}$Mn	Fully completed	- First application of optical pumping in ISCOOL at ISOLDE [2] - Onset of collectivity towards $N = 40$ studied via the magnetic moments [3, 4] quadrupole moments [2] and mean-square charge radii [5] - Firm spin assignments of low-spin and high-spin isomers in ^{58,60,62,64}Mn [4] - Part of PhD thesis of C. Babcock [6] and H. Heylen [7]
IS519	$^{63-79}$Zn	Fully completed	- Observation of unexpectedly large difference in charge radius between the ground state and isomer in ^{79}Zn$_{49}$ [8] - Structural evolution studied from magnetic and quadrupole moments [9, 10] - Cross-shell proton excitations investigated via Zn charge radii [11] - Part of Phd thesis of C. Wraith [12] and L. Xie [13]
IS529	$^{50,52-54}$Ca	See section 3.1	- Development of a sensitive setup to study very exotic calcium isotopes [14] - Part of Phd thesis of R.F. Garcia Ruiz [15]
IS568	$^{58-68,70}$Ni	Articles in preparation	- First measurement of charge radii of radioactive Ni isotopes, new moments for 2 isotopes [16, 17] - Study of the ^{68}Ni charge radius in relation to its dipole polarizability [18] - Part of PhD thesis of L. Xie [13] and S. Kaufmann [19]
IS573	$^{108-134}$Sn	Articles in preparation	- Established and explained the kink in the charge radii at $N = 82$ in Sn [20] - Simple but surprising linear and quadratic mass-dependent trends of quadrupole moments and isomer shifts [21] - Study of the doubly-magic-plus-one-neutron nucleus ^{133}Sn [22] - Part of PhD thesis of C. Gorges [23] and L. Vázquez-Rodríguez [24]
IS617	$^{26-32}$Al	Articles in preparation	- First measurement of charge radii of radioactive Al isotopes, new moments for 2 isotopes [25] - Follow-up proposal to study ^{26g,m}Al accepted at IGISOL PAC
IS623	$^{68-74}$Ge	Data analysis ongoing	- Will be part of thesis of A. Kanellakopoulos
IS635	$^{112-134}$Sb	Data analysis ongoing, see section 3.2,	- Will be part of thesis of S. Lechner
IS649	$^{44-50}$Sc	Data analysis ongoing	- Will be part of thesis of S. Bai
⋆	$^{197-209}$Bi	Articles in preparation	- The relevance of the ^{208}Bi magnetic moment for testing bound-state strong-field QED [26] - The hyperfine anomaly in Bi-isotopes [27]

⋆ Note that the Bi-data are the by-product of a collaboration to understand unexpected observations of the IS608 in-source laser spectroscopy experiment.

3 Status report on experiments with remaining shifts

As illustrated in previous section, the COLLAPS collaboration completed most of its proposals at the beginning of LS2. For two experiments, there are nevertheless shifts outstanding which we would wish to keep: 17 shifts for IS529 (Ca - ROC technique) and 6 shifts for IS635 (Sb). In this section we demonstrate that the physics cases originally endorsed by the INTC remain significant. Additionally, we highlight the technical developments which are being undertaken to deal with the issues encountered during the previous run of IS529.

3.1 IS529

- Title: Spins, Moments and Charge Radii beyond ^{48}Ca
- Spokesperson: M.L. Bissell
- Outstanding shifts: 17

In the evaluation of the first addendum to the IS529 proposal, the INTC recommended that the 'Radioactive detection of Optically pumped ions after state selective Charge exchange' (ROC) technique should be developed and applied to ^{53,54}Ca. In 2015, a first attempt was made to measure these isotopes using the ROC technique. During this run it was possible to demonstrate the extreme sensitivity of the technique and to validate our simulations of the two step optical pumping procedure for the measurement of hyperfine structures [14]. However, the yields of ^{53,54}Ca observed at that time were significantly below the level initially predicted and subsequently observed by ISOLTRAP, preventing further measurement. Also a number of potential areas for improvement of the setup were identified, including the development of two new tape stations. In 2016, it was concluded that due to the need for further technical development and the large number of open proposals requiring the COLLAPS setup, as summarized in table 1, the project should be delayed until long shutdown 2.

Ongoing relevance of the physics case

Since the report of our surprising observations on the charge radii of $^{49-52}$Ca [28], also the neutron-deficient $^{36-38}$Ca isoptes were measured [29] and a substantial theoretical effort has gone into understanding all these results [30, 31, 32, 33]. Based on these varied theoretical developments, the description of nuclear charge radii has advanced across the nuclear chart. Recent developments in density functional theory [31], aimed at reproducing the $^{49-52}$Ca charge radii, have aided the description of charge radii in iron [34], cadmium [35] and tin [20]. Furthermore, the development of a new model of charge radii, based on shell-model considerations and the assumption of a halo-like character of certain orbits [33], has also found applicability in the description of the ground state properties of Mn [5]. This key position of the Ca isotopic chain in our understanding of nuclear structure only heightens the relevance of further experimental effort.
Phenomenologically, our understanding of the impact of orbital occupancy on nuclear charge radii has also developed [11], bringing significant new insight into the discussion of sub-shell closures observed in charge radii. In conclusion, the measurement of $^{53-54}$Ca

between the $N = 32$ and $N = 34$ sub-shell closures has become more relevant than ever, in light of these substantial theoretical advances.

Experimental feasibility and technical developments

A thorough analysis of our β^- counting rates was performed after the 2015 beam time. From this analysis it became apparent that the yield of ^{54}Ca was below our detection limit of, at that time, $0.1/\mu$C, in contrast to the previously measured yield of $10/\mu$C. Further to this analysis, a detailed study of our detector background was undertaken at the end of 2015. Based on this study, a number of areas for improvement of the setup were identified, with the objective of pushing our sensitivity to below the $0.1/\mu$C level. Firstly, new tape stations would have to be developed to improve reliability and accommodate a significantly longer tape. In this way, we would be able to perform multiple hour measurements without recycling over previously used tape. Secondly, although good transmission to the ion β^- detection station was achieved, room for improvement remained at the atom β^- detection station, where the transmission was lower by a factor of 3. To improve this situation it was concluded that an offline ion source should be developed in order to thoroughly investigate losses and optimize transmission prior to a future run. Finally, based on the observed energy and timing spectra of background in our β^- detectors following proton impact, optimization of the detector form and shielding should take place.

With regard to these developments a new tape system has been designed and is now under construction at MPIK Heidelberg. The Ca ion source has been constructed, fully characterized and is now installed at COLLAPS. Finally, detector simulations are underway in order to minimize the sensitivity to the observed background. Therefore, we conclude that these developments will permit the measurement of ^{53,54}Ca within one run following long shutdown 2. It is not expected that we would require additional shifts, unless the yield of ^{54}Ca is found to be significantly lower than $0.1/\mu$C.

3.2 IS635

- Title: Nuclear quadrupole moments and charge radii of the $_{51}$Sb isotopes via collinear laser spectroscopy
- Spokespersons: Z.Y. Xu, D.T. Yordanov
- Outstanding shifts: 6

In October 2018, the atomic hyperfine spectra of $^{112-134}$Sb were successfully measured, including 22 ground states and 11 long-lived isomers. An example of the data quality obtained for ^{134}Sb can be seen in Fig. 1. In addition to confirming the magnetic moments known in literature, for the first time also quadrupole moments and changes in mean-square charge radii from $N = 61$ up to $N = 83$ were determined. Data analysis is still ongoing but our preliminary quadrupole moments of the $7/2^+$ states show excellent agreement with the shell-model calculation considering only proton and neutron single-particle orbits within the 50–82 shell [36], see Fig. 2. Measuring ^{135}Sb was unfortunately not possible within the available beam time due to the overwhelming contamination at

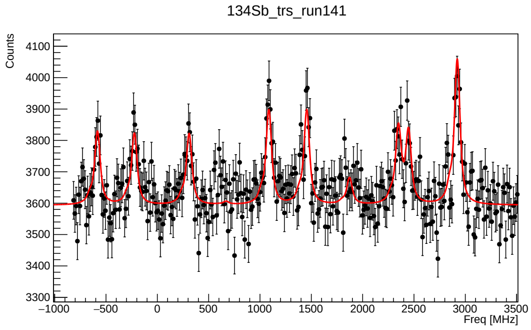

Figure 1: Experimental spectrum of ^{134}Sb obtained in 8 hours.

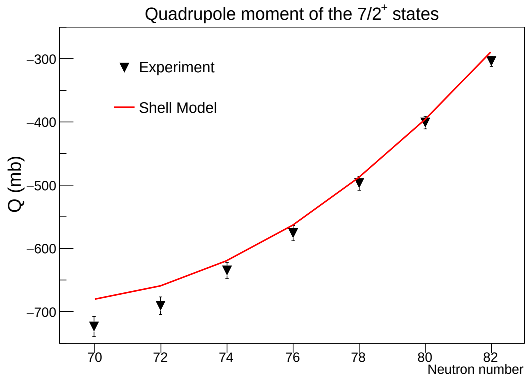

Figure 2: Experimental quadrupole moments of the $7/2^+$ states in antimony isotopes compared with the shell-model calculations [36]. Data from $N = 74$ onwards is newly measured from this work.

mass 135. We argue that ^{135}Sb is a key isotope to address two physics questions of the original proposal which cannot be discussed with the currently available data.

Ongoing relevance of the physics case

Although a discontinuity in the mean-square charge radii trend is a common feature when crossing a shell closure, a microscopic and universal understanding of this phenomenon has proven to be challenging. Recently, it was demonstrated that the Fayans energy density functional provides a satisfactory description of the kink at $N = 82$ in the Sn ($Z = 50$) [20] isotopic chain. A systematic study of the Z-dependence of this kink requires to extend the measurements to the antimony isotopic chain. Although, the $N = 82$ shell closure was in principle crossed by measuring ^{134}Sb$_{83}$, the even-N ^{135}Sb$_{84}$ isotope is essential to establish the change in slope at $N = 82$ without any assumption on the strength of the odd-even staggering.

In addition, the microscopic configuration of the low-lying states in antimony beyond $N = 82$ is not yet well understood. In even-N antimony isotopes below $N = 82$, the first $7/2^+$ and $5/2^+$ states are interpreted as $\pi g_{7/2}$ and $\pi d_{5/2}$ single-particle states, respectively. However, the energy spacing between $7/2^+_1$ (ground state) and $5/2^+_1$ (first excited state) in ^{135}Sb shows anomalous systematics compared to that in less neutron-rich antimony isotopes [37]: it reduces from 962 keV in ^{133}Sb down to 282 keV in ^{135}Sb. Two scenarios have been proposed to interpret this sudden decrease: either it is due to the shift of $\pi d_{5/2}$ single-particle orbit relative to $\pi g_{7/2}$ [37] or the $5/2^+$ state is pushed down in energy by mixing with other seniority configurations [38]. Establishing the purity of the $7/2^+$ ground state via a magnetic and quadrupole moment measurement, is an important step to shed light on this question. It is worth to note that unlike antimony isotopes with $N < 82$, no spectroscopic factors have been measured for ^{135}Sb (or any state beyond $N = 82$).

Experimental feasibility

With the knowledge on the beam purity at $A = 135$ and the COLLAPS' efficiency for laser spectroscopy on antimony atoms obtained during last run, we calculated that 6 shifts will not be sufficient to get clean and reliable results on ^{135}Sb in the current conditions. We are exploring several options to improve the situation and therefore ask to keep the available shifts. If the outcome of our exploration points to a need for additional shifts, an addendum will be submitted.

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