CERN-INTC-2022-048 / INTC-P-646
27/09/2022

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Laser spectroscopy of neutron-rich indium isotopes beyond $N = 82$

September 27, 2022

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Abstract: Nuclear properties of ground- and isomeric states of the neutron-rich $^{131-134}$In ($Z = 49$) are proposed to be measured using Collinear Resonance Ionization Spectroscopy (CRIS), yielding their electromagnetic moments and changes in

mean-square charge radii. The measurements will offer new and complementary insights into how the nuclear structure of a proton hole at $Z = 50$ evolves beyond the neutron closed shell $N = 82$. Our results will provide essential input to guide developments of density functional theory and *ab initio* calculations in this frontier region of the nuclear chart.

Requested shifts: 16 shifts with protons (+ 3 without for setup).

1 Motivation and previous experiments

Isotopes in the vicinity of doubly magic nuclei are particularly important systems in our understanding of atomic nuclei. Their simpler structures are more computationally tractable and measurements of them provide critical guidance to develop inter-nucleon interactions and nuclear many-body methods [1, 2, 3, 4].

The indium ($Z = 49$) isotopic chain, with 1 proton less than proton-magic tin ($Z = 50$), offers a compelling system to study the evolution of nuclear properties both between and beyond the suggested neutron closed shells at $N = 50$ and $N = 82$ [5, 6, 7].

The sustained interest in this region of the nuclear chart has motivated complementary studies at ISOLDE, including laser spectroscopy studies performed by the COLLAPS collaboration on the nearby cadmium ($Z = 48$) [8, 9], tin ($Z = 50$) [10, 6], antimony ($Z = 51$) [11] and tellurium [12] chains. In addition, decay spectroscopy studies were undertaken at the ISOLDE Decay Station (IDS) on the neutron-rich indium isotopes $^{133-135}$In [13, 14] .

Moreover, two successful experiments on short-lived indium isotopes, between ^{101}In($N = 52$) and ^{131}In($N = 82$), have been performed using the Collinear Resonance Ionization Spectroscopy setup (IS639 [15] and addendum [16]). Our first results, which include the electromagnetic moments of neutron-rich isotopes and charge radii, were published recently [7, 17]. Additional articles reporting further charge radii, the electromagnetic moments of neutron-deficient isotopes and the properties of high-spin isomers are in progress.

In a shell-model picture, the ground states of even-N indium isotopes should be predominately described by a proton hole in the $g_{9/2}$ orbital. In addition, low-lying $1/2^-$ isomeric states, whereby a proton is excited from the $\pi p_{1/2}$ to $\pi g_{9/2}$ orbital, appear consistently in all even-N indium isotopes studied to date. The simultaneous existence of these two nuclear states allow the evolution of both single-particle and collective behaviour at extreme proton-to-neutron ratios [7] to be probed. Long-lived isomers can also be formed by the breaking of a neutron pair to create nuclear configurations of high nuclear spin ($I > 19/2$) in the vicinity of $N = 82$ [18].

Furthermore, studying its odd-N isotopes enables complementary aspects of the proton-neutron interaction to be investigated. These isotopes exhibit rich isomerism, forming nuclear states of different spin. These odd-N isotopes are suggested to be dominated by the interaction of the $\pi g_{9/2}$ and $\pi p_{1/2}$ proton states with multiple single-particle neutron states formed by the gradual filling of the $\nu s_{1/2}$, $\nu d_{3/2}$, $\nu g_{7/2}$, and $\nu h_{11/2}$ orbitals with increasing N.

The nuclear electromagnetic properties of ground states and isomers of indium isotopes are unknown beyond $N = 82$. Both the $9/2^+$ ground- and $1/2^-$ isomeric states are predicted to appear for the odd-even isotopes ^{133,135}In. For the odd-odd ^{132,134}In, their nuclear spins are predicted to be (7^-) [19, 14], dominated by a $\pi g_{9/2} \otimes \nu f_{7/2}$ configuration [20].

The results for the magnetic moments and quadrupole moments of the $I = 9/2^+$ states of odd-even isotopes obtained during the previous IS639 CRIS experiment are shown in Figure 1 [7]. Concurrent to our experimental developments, impressive progress has been made in describing nuclear properties within the DFT framework and by *ab initio* methods [21, 22, 7]. Figure 1 compares the experimental values with the theoretical results from Density Functional Theory (DFT), and Valence Space In-Medium Similarity Re-normalization Group (VS-IMSRG) calculations. DFT calculations include both Hartree–Fock (HF) and Hartree–Fock–Bogoliubov (HFB) approaches. The inclusion of time reversal-symmetry breaking terms was shown to be essential to describe the observed magnetic moments [7]. VS-IMSRG calculations were performed using two different forces derived from chiral effective field theory[23, 24, 25], labeled as 1.8/2.0(EM) and $\mathrm{N2LO_{GO}}$. Although the magnitude of the electromagnetic moments is not reproduced, these calculations closely describe the observed relative trends. No effective factors were used in the employed calculations.

DFT and *ab initio* predictions of the magnetic dipole and electric quadrupole moments of indium beyond $N = 82$ are also included in Figure 1 [26], Details of the theoretical approaches can be found in Refs. [7, 27, 28] Notably, the magnitude of the electromagnetic moments of ^{133}In, with a neutron pair in the $f_{7/2}$ orbital, are predicted to be similar to that of ^{129}In, which has two neutron holes in the $h_{11/2}$ orbit. Moreover, a similar trend to that observed towards $N = 82$ is predicted at $N = 90$. An abrupt change of nuclear structure properties at $N = 90$ has been suggested from other theoretical and experimental studies [29, 30].

The measurements proposed here will provide the first insights into how nuclear structure evolves beyond $N = 82$ for an isotope chain below the $Z = 50$ shell closure allowing the predictions from these state-of-the-art calculations to be tested. In addition to investigating how the single-particle and collective behaviour of these nuclei evolves beyond $N = 82$ through their electromagnetic moments, their changes in mean-square charge radii will give the first information on this observable for an isotope chain with $Z < 50$ across this shell closure.

2 Objectives, experimental details and beam time request

The neutron-rich indium isotopes $^{131m-134}$In are proposed to be measured using CRIS yielding the following properties for the first time:

- ^{131m2}In ($21/2^+$): μ, Q_s, $\delta\langle r^2\rangle$ [31]
- ^{132}In (7^-): μ, Q_s, $\delta\langle r^2\rangle$ [19]

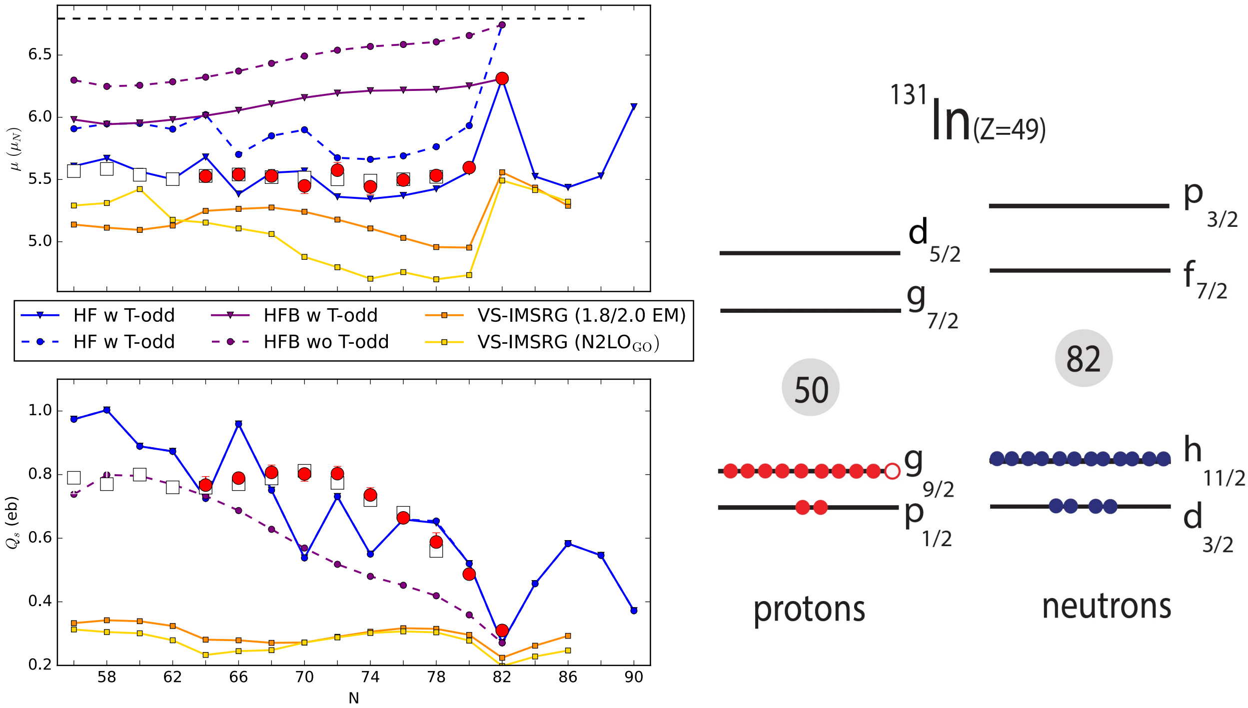

Figure 1: *Left*: Experimental nuclear magnetic dipole moments (top) and electric quadrupole moments (bottom) of the $9/2^+$ ground states in even-N indium isotopes, shown alongside *ab initio* and DFT calculations. DFT and *ab initio* predictions are shown for $^{133-135}$In with additional calculations for ^{137,139}In from DFT. The black dashed line denotes the unquenched Schmidt limit. *Right*: Shell model orbits for ^{131}In, $Z = 49$ and $N = 82$.

- ^{133g}In ($9/2^+$): μ, Q_s, $\delta\langle r^2\rangle$ [13]
- ^{133m}In ($1/2^-$): I, μ, $\delta\langle r^2\rangle$ [13]
- ^{134}In (7^-): μ, Q_s, $\delta\langle r^2\rangle$ [14].

Bunched indium ion beams will be delivered to CRIS where they will be neutralized in-flight through charge-exchange collisions with a sodium vapour. Any residual ions following this are deflected away before the neutral bunches enter an ultra high-vacuum region where they are collinearly overlapped with two lasers.

Two atomic transitions in neutral indium with similar wavelengths (246.0 nm, 246.8 nm) were used in previous CRIS experiments [7]. A sketch of these atomic transitions is shown in Figure 2. The different angular momenta and sensitivities of the states involved in these two transitions enable precise measurement of all the nuclear observables of interest in addition to allowing each hyperfine structure transition to be assigned to the nuclear state from which it originates. As the wavelengths of these transitions are very similar, switching between them is possible with minimal intervention. When the first-step laser is on resonance, indium atoms are excited to either the $8S_{1/2}$ or $9S_{1/2}$ states. These excited atoms can be efficiently non-resonantly ionized with a single 1064-nm photon, produced by a high pulse-energy Nd:YAG laser. Further resonant excitation to a Rydberg state to enable field ionization, as developed previously, is also possible [32].

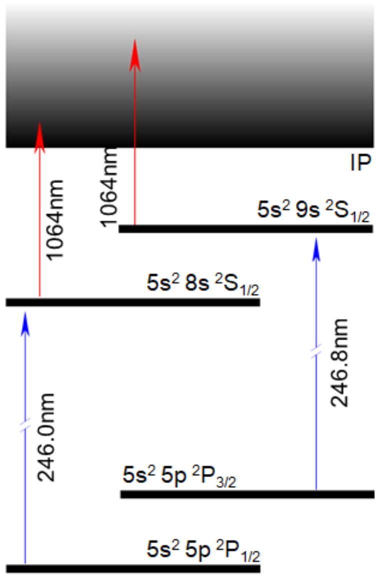

Figure 2: Laser ionization scheme proposed for the study of neutron-rich In isotopes. These schemes were successfully used during previous CRIS experiments [7].

The resulting resonant indium ions are then steered onto an ion detector where they are counted as a function of spectroscopic laser frequency. The short half-lives (< 200 ms) and large β-decay energy of $^{131-134}$In ($Q_\beta > 13$ MeV), with respect their isobaric contaminants, open up the possibility of using β detection. This approach was successfully used to measure ^{52}K despite significant stable ^{52}Cr contamination (> 10 pA) [33]. Additionally, these neutron-rich isotopes can decay through beta-delayed neutron (βn) emission. Hence, neutron detection could be a highly selective and efficient method to circumvent the intense isobaric contamination, which is dominated by stable and long-lived isotopes of Ba and Cs. Based on the design of the ISOLDE Decay Station (IDS), a dedicated β-decay station for CRIS is being built at KU Leuven [34], and will be commissioned at the beginning of 2023. In addition, an existing neutron detection array [35] from Institut Laue-Langevin (ILL) in Grenoble could be installed at the end of the CRIS beamline to enable neutron detection. Either of these would provide a means to reduce the detrimental impact of the significant contamination expected at these masses on the spectra measured in this campaign.

Beam time request

In total, we request 16 shifts with protons using a UC_x target constructed with a neutron converter and quartz transfer line. Preceding this, we request 3 shifts to perform beam tuning, charge-exchange cell heating and laser/atom interaction optimization. The details of the beam production and the required shifts for this proposal are summarized in Table 2. The yields are taken from the ISOLDE Yield database and correspond to

Isotope	I	Half life (ms)	Yield (ions/μC)	Shifts	Q_β (MeV)
^{115}In	$9/2^+$	stable	$> 10^5$	3 (setup)	0
^{131m2}In	$(21/2^+)$	300	200	3	unknown
^{132}In	(7^-)	194(4)	8000	2	14.14 (6)
^{133g}In	$(9/2^+)$	162(2)	900	2	13.18 (20)
^{133m}In	$(1/2^-)$	162(2)	300	3	unknown
^{134}In	(7^-)	118(6)	100	6	14.46 (20)
height					

Table 1: Isotopes of interest, their spins and half-lives [31, 19, 13, 14], yields and shifts requested. The quoted yields for the ground states are taken from the ISOLDE Yield Database where a UC_x target with neutron converter is used in combination with RILIS. The yield of ^{131m,133m}In was estimated using experimentally observed ratios in ^{129,131}In during the IS639 experiment. The requested shifts include the time needed for regular calibration measurements with the reference isotope ^{115}In, however 3 shifts (without protons) preceding the experiment are requested for beam tuning, charge-exchange cell heating and laser/atom interaction optimization.

neutron-converter yields. The use of a LIST would massively suppress surface-ionized contaminants (Cs and Ba) which are strongly produced in this mass range. However, yield measurements of $^{131-134}$In utilizing a LIST in early 2022 demonstrated a LIST-mode loss factor of 35-50 with respect to existing on-converter yields [36].
The required shifts were estimated assuming an overall experimental efficiency of 0.05 % and a background suppression factor of 10^{-6}. These values were taken from the previous experiments on indium at CRIS.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
CRIS experiment	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed CRIS installation.