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

Laser Spectroscopy of Tin and Cadmium: Across $N = 82$ and Closing in on $N = 50$

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Abstract:

We propose to study the isotopes of tin starting in proximity of $N = 50$ up to and beyond $N = 82$, as well as the "magic-plus-one" nuclei of cadmium at both shell closures. The objective is to determine model-independent properties of ground and isomeric states by high-resolution laser spectroscopy, which are essential for understanding the structure of nuclei and their astrophysical importance in this region of the nuclear chart.

keywords: tin, cadmium, electromagnetic moments, radii, COLLAPS

Requested shifts: 44 shifts of radioactive beam and 6 shifts of stable beam

1 Introduction

Our recent measurement by collinear laser spectroscopy at ISOLDE-CERN revealed a unique sequence of ten electric quadrupole moments in the isotopes of cadmium increasing linearly with respect to the atomic mass number [1]. Such an extraordinary behavior had indeed been anticipated since the middle of the 20^{th} century when the nuclear shell model suggested it for extreme cases of nuclei with a single open shell. This simplistic view of the early shell model was considered unrealistic due to the known complexity of the nuclear state. Only under rare circumstances, as in the isotopes of cadmium, would quantum mechanics favor a simple structure in a chain of complex nuclei. Yet, the linear increase of their quadrupole moments was found to extend well beyond a single shell - a result never predicted before. The current understanding of this phenomenon is essentially a generalization of the original picture due to a competition between multiple nuclear states. However, a solid theoretical interpretation is still to be proposed. Furthermore, such theoretical studies will greatly benefit from experimental data on the more exotic isotopes of cadmium, and especially on the "magic" tin isotopes. Access to those nuclei has become available in recent years as a result of technological advances in laser equipment and radioactive-beam production. The measurements proposed here will certainly benefit from these favorable conditions.

2 Physics case

The isotopes of cadmium and tin are of high scientific interest in at least two contemporary research areas. First, they are desirable probes for nuclear-structure studies due to the access to three magic numbers: $Z = 50$, $N = 50$, and $N = 82$. Second, they are key ingredients for understanding the stellar nucleosynthesis and neutron stars in particular [2], which in turn is also related to closed shells in nuclei [3–5]. The specific objectives of this proposal are discussed in the following sections.

2.1 Quadrupole moments

Combined effort over several experimental studies, including three separate laser-spectroscopy experiments [6–8], supply the currently know ground- and long-lived isomeric-state electromagnetic moments of $^{108\text{-}132}$Sn. The interest in the quadrupole moments of tin was considerably increased after the discovery of the linear alignment of ten $11/2^-$ quadrupole moments in cadmium [1], as shown in Fig. 1 (a). Preliminary interpretation of these suggests the relevance of the shell-model prediction in Eq. (1), where the quadrupole moment Q generated on an orbital with an angular momentum j increases linearly with respect to the number of nucleons n on that orbital.

$$\langle j^n|\hat{Q}|j^n\rangle = \frac{2j+1-2n}{2j-1}\langle j|\hat{Q}|j\rangle. \tag{1}$$

However, the peculiarity of the cadmium case is that the linear increase from ^{111}Cd to ^{129}Cd involves the addition of 18 neutrons, much more than the capacity of 12 neutrons in the $h_{11/2}$ shell. It is currently unknown whether this is related to the two proton holes of

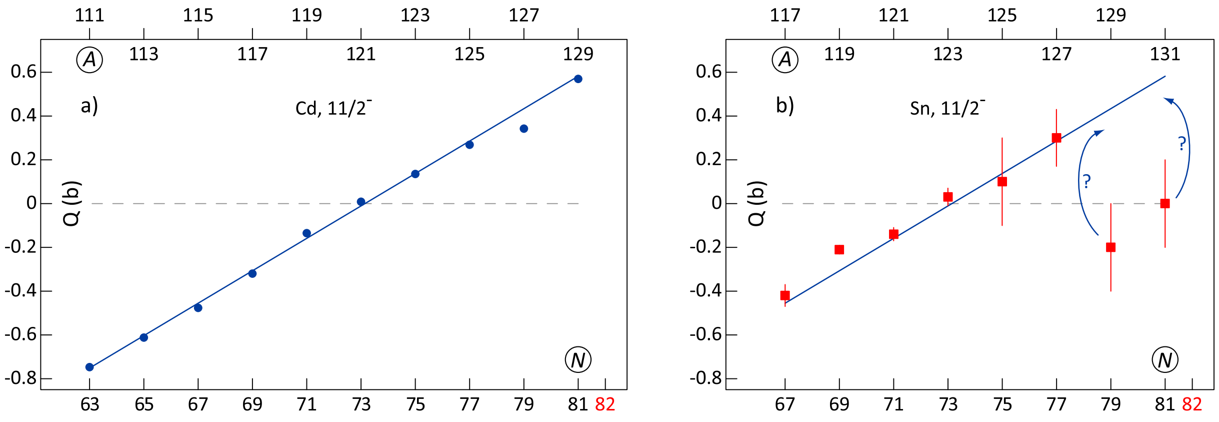

Figure 1: Electric quadrupole moments of the long-lived $11/2^-$ states in cadmium (a) and tin (b). A straight line is fitted through the quadrupole moments of cadmium, consistent with Eq. (1). For comparison, the same line is also displayed in the inset (b).

the $Z = 50$ shell, or it is a property only of the neutron distribution. The natural solution to this problem is to look at the $11/2^-$ states in the tin isotopes where the proton shell is closed and therefore its influence on the quadrupole moments should be considerably reduced. The relevant nuclear moments have been measured before, but the accuracy and precision of the measurements, as evident from Fig. 1 (b), is such that conclusions can not be made with certainty. The quadrupole moments of ^{117}Sn, ^{121}Sn, and ^{123}Sn are measured with a reasonable precision [6] and indeed fall on a straight line. The deviation from the line at ^{119}Sn [9] is possibly due to systematic uncertainties arising between the separate experiments. One has to note that the negative sign of the moment in this case is assumed, not measured. The measurements on the remaining $^{125\text{-}131}$Sn [6, 8] are too imprecise to be meaningful. Either of these could be consistent with zero, although the moments of ^{125}Sn and ^{127}Sn do fall on the straight line, which of course could only be accidental considering their large error bars. The quadrupole moments in the range $^{117\text{-}131}$Sn need to be remeasured in order to reveal the true structure of their $11/2^-$ states. A linear trend is certainly expected, however, the critical question is the number of isotopes involved in it.

2.2 Electromagnetic moments and charge radii beyond $N = 82$

A key objective of this proposal is to study the nuclei of tin and cadmium beyond $N = 82$. Former laser-spectroscopy measurements on indium [10] and tin [8] could not be propagated this far due to limitations in terms of experimental sensitivity and radioactive-beam production and purification. Nowadays ISOLDE provides solutions to these problems, namely: a neutron converter, a quartz transfer line [11], an efficient laser ionization [12], and bunched beams from a radio-frequency Paul trap [13–15]. These were key advantages for the success of our recent measurement on the isotopes of cadmium extending up to the magic ^{130}Cd. Under the current experimental conditions ^{131}Cd and $^{133\text{-}136}$Sn are within reach. The ground states of these nuclei should be determined by the orbitals

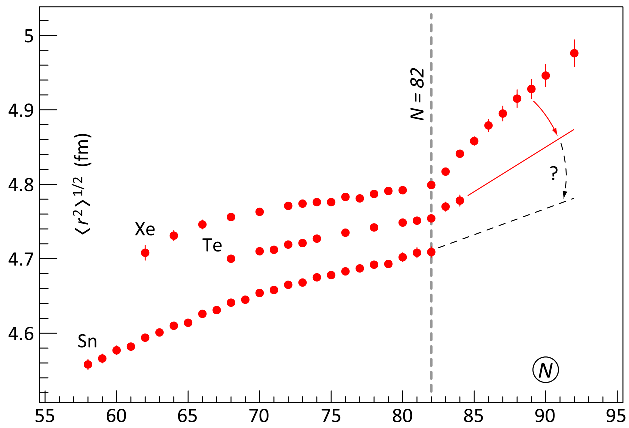

Figure 2: Rms charge radii of xenon, tellurium, and tin. The data are taken from the combined analysis of Fricke and Heilig [18] with the addition of recent results on tellurium [16] and tin [8]. Only ground states are depicted.

of the shell above the $N = 82$ shell gap. Laser spectroscopy is capable of detecting the corresponding spin change and probing the nuclear configuration through their electromagnetic moments. Furthermore, the charge radii are of particular importance, as evident in Fig. 2. From samarium to xenon the charge-radii trends exhibit a well-pronounced and quite similar kink at the shell closure. However, the measurements on tellurium [16] indicate a weakening of this effect, which may be correlated with statements made previously about “quenching” [5, 17] versus “restoration” [3] of the $N = 82$ shell gap. Mean-field theory also supports a flattening of the charge-radii trends across $N = 82$ for tin and cadmium. Laser spectroscopy will certainly answer this question.

2.3 Magic-plus-one nuclei

Three nuclei withing the proposed range of studies carry a single nucleon on top a closed-shell core, namely ^{99}Cd, ^{131}Cd, and the doubly-magic-plus-one-neutron ^{133}Sn. Such cases act as pillars for improving the nuclear theory away from the valley of stability. Each of these would probe a different aspect of the nuclear shell structure due to the involvement of three different magic numbers: $Z = 50$, $N = 50$, and $N = 82$.

2.4 Towards ^{100}Sn

The ground-state properties of the neutron-deficient tin nuclei have been studied down to ^{108}Sn [7]. We propose to extend the knowledge to the very light isotopes in the range $^{104\text{-}107}$Sn. The moments and radii from laser spectroscopy will certainly contribute to a better understanding of the nuclear structure in the region.

3 Experiment

We have previously justified [19] a general feasibility limit of laser spectroscopy experiments on bunched beams as being 10^3 ions/μC required for even-even isotopes, and 10^4 ions/μC required for isotopes with a hyperfine structure. The assumptions in this estimate are quite modest. First, only half of the proton pulses are available (once every 2.4 s) with only half the intensity (1.5×10^{13} protons/pulse). Second, the efficiency for photon detection is conservatively taken as 10^{-4} photons/atom. The production rates in the entire range from ^{104}Sn up to ^{136}Sn [11] are higher than the stated feasibility limit, even with the use of a "neutron converter".

Historically three transitions in the atomic system of tin have been used for laser spectroscopy [6–8]. For most isotopes, especially for those whose magnetic moments are known reasonably well, we consider the transition $5p^2\ ^1S_0 \rightarrow 5p6s\ ^1P_1$ at 453 nm due to its higher sensitivity to the quadrupole moment. For isotopes whose magnetic moment is unknown or its precision needs to be improved we consider complementary measurements in the transition from the ground state $5p^2\ ^3P_0 \rightarrow 5p6s\ ^3P_1$ at 286 nm. The reason for such a combined approach is that the $^1P_1$ with respect to the $^3P_1$ state offers about four times larger electric field gradient, but the magnetic field at the nucleus is about twenty times smaller [7]. The 453-nm transition initiates from a metastable state which can be populated in a "quasi-resonant" charge exchange with sodium [7].

The measurements on the two proposed cadmium isotopes would require a dedicated experiment each. The reported yields are: 4.5×10^2 ions/μC for ^{99}Cd and 1.0×10^3 ions/μC for ^{131}Cd [20]. Our recent measurements on $^{100\text{-}130}$Cd [1] showed a very high detection efficiency in the ionic transition $5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{3/2}$ at 215 nm, as high as one photon in five hundred ions (2×10^{-3}). This boosts the sensitivity twentyfold with respect to the assumptions above, meaning that both cadmium isotopes would fall within the range of feasibility. However, in the case of ^{131}Cd one has to consider the isobaric contamination, which might require the use of a neutron converter, thereby decreasing the yield with a factor from 3 to 10. In this estimate the cited reduction is typical for a conventional converter unit. However, ISOLDE is currently developing an advanced converter design. Assuming an increased performance in terms of purity, and a yield loss on the lower limit of the old design (factor of 3 or better), the measurements on ^{131}Cd would be possible. Considering the initial tests of a new-converter design such target performance is indeed expected.

Finally, one has to point out a convenient coincidence in terms of laser wavelengths. Like cadmium, tin has an ionic transition at 215 nm starting from the ground state $5p\ ^2P_{1/2} \rightarrow 5s5p^2\ ^4P_{1/2}$. At this point we consider characterizing this transition off-line as a possible alternative to the 286 nm transition in the atom. If the magnetic moment and the charge radius are well resolved it will be possible to benefit from a very high sensitivity also for the measurements on tin.

4 Beam-time request

Herewith, we request **44 shifts of radioactive beam** and **6 shifts of stable beam** for measuring spins ,electromagnetic moments, and rms charge radii of the isotopes of tin and cadmium. This work is aimed to be carried out as follows:

• one experiment of 10 shifts for $^{104\text{-}113}$Sn, using a LaC_x target, RILIS, HRS and ISCOOL;

• one experiment of 12 shifts for $^{121\text{-}136}$Sn, using a UC_x target, RILIS, HRS and ISCOOL;

• one experiment of 10 shifts for ^{99}Cd, using a LaC_x target, RILIS, HRS and ISCOOL;

• one experiment of 12 shifts for ^{131}Cd, using a UC_x target, RILIS, HRS and ISCOOL;

• each experiment would require 1 shift of stable beam for calibration measurements;

• 2 shifts of stable tin beams are needed for characterization of the 215-nm transition;

Summary of requested shifts: 44 shifts of radioactive beam and 6 shifts of stable beam are being requested for the study of $^{104\text{-}136}$Sn, ^{99}Cd, and ^{131}Cd.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

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

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant to the fixed COLLAPS installation.