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

for ISOLDE Proposal INTC-P-378

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

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Abstract:

This Letter of Clarification elaborates on the potential impact of laser spectroscopy on the theoretical modeling of the tin isotopes. Furthermore, the beam-time estimate of 44 shifts of radioactive beam and 6 shifts of stable beam is discussed transparently and in greater detail with respect to the original proposal.

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

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

1 Introduction

This proposal [1] was defended at the 44th meeting of the INTC held on June 26, 2013. The referees regarded the physics case as sound and potentially fruitful [2]. A detailed justification for the requested number of shifts has been requested, as well as an additional input from theory supporting the physics case on the tin isotopes.

2 Input from theory

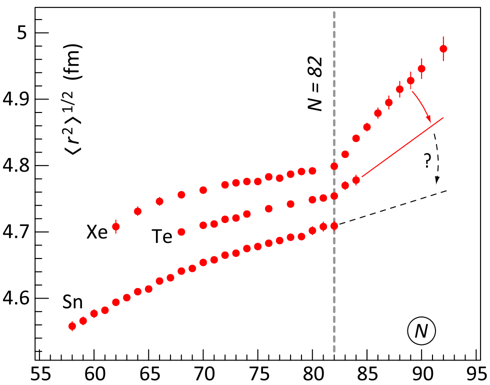

Figure 1: Experimental rms charge radii of Xe, Te, and Sn [3–6].

Nuclear charge-radii trends from samarium to xenon exhibit a well-pronounced and rather similar kink at the $N = 82$ shell closure. Recent measurements on tellurium [5] suggest a weakening of this effect in proximity of $Z = 50$, as indicated in Fig. 1. Charge radii measurements on tin and cadmium would be an essential ingredient for resolving the ongoing dispute on "quenching" [7, 8] versus "restoration" [9] of the $N = 82$ shell gap. Mean-field theory is capable of reproducing the shell effect on the radius across the nuclear chart. Regarding the region of interest one may refer to Relativistic Mean-Field (RMF) [10] and Hartree-Fock-Bogoliubov (HFB) [13] calculations from the recent past. Both show no indication of a kink on either the tin or the cadmium radii at the magic number $N = 82$. In contrast both suggest such an effect at $N = 50$, which appears to be much more pronounced in the RMF radii. It is clear that the absence of a shell effect at $N = 82$ can not be considered a prediction since the same calculations fail to reproduce the experimentally known kink in the xenon radii [4] (Fig. 1). Consequently a dedicated theoretical inquiry was launched to support the physics case of this proposal. HFB calculations using the HFODD code [11] and the energy-density functional UNEDF1 [12] showed a good agreement with the experimental data on xenon with a well pronounced shell effect. This is confirmed in Fig. 2 where the calculated charge radii of xenon, tellurium, tin, and cadmium across $N = 82$ are presented. The model predicts no kink for tin and cadmium across the shell closure. Furthermore, this result appears independent from Lipkin-Nogami projection and the choice of different Skyrme parametrizations, such as SkI4, SkM*, and UNEDF0. The radii measurements proposed here are expected to either establish confidence in the UNEDF1 predictions, or indicate the need of considering experimental data on shell gaps. This indeed is highlighted as a future step for improvement of the UNEDF functionals [12].

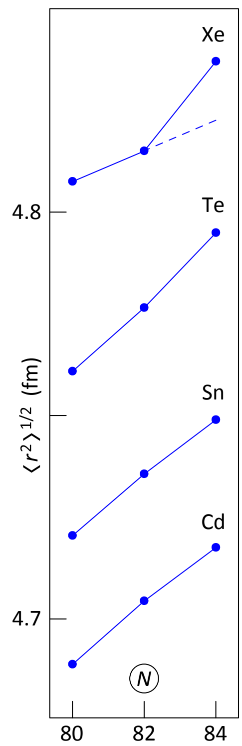

Figure 2: HFB*.

*HFB calculation of rms charge radii across $N = 82$ using HFODD [11] and UNEDF1 [12].

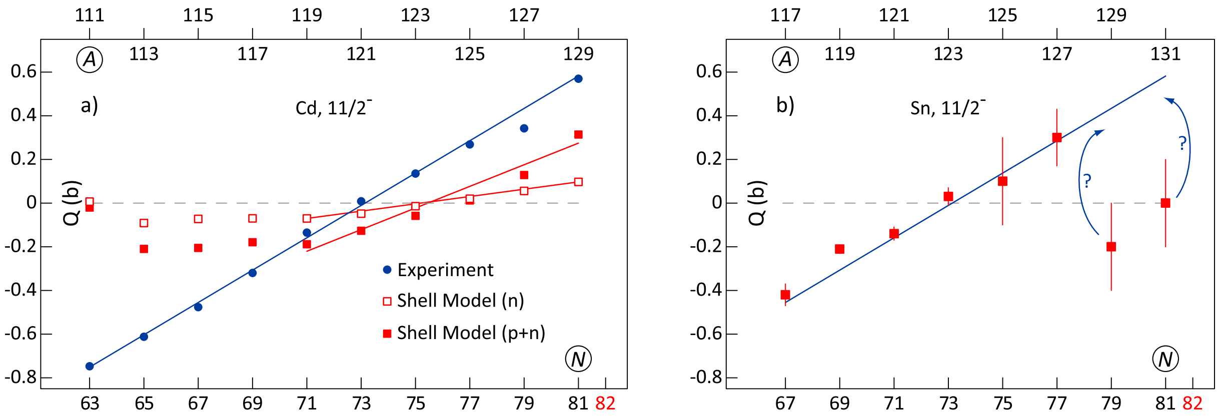

Figure 3: $11/2^-$ quadrupole moments of cadmium (a) and tin (b). A straight line is fitted through the quadrupole moments of cadmium, consistent with Eq. (1) and displayed in the inset (b) for comparison. Shell-model predictions are included in plot (a).

Another exciting feature of the tin isotopes is the expected linear increase of the $11/2^-$ quadrupole moments. Even though the HFB calculation discussed here also offers an interpretation of the quadrupole moments in Fig. 3 (a), the following discussion will be carried out in the context of the spherical shell model. The linear increase of the quadrupole moments of cadmium resembles the expectation from filling the $h_{11/2}$ shell according to:

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

However, two important features need to be explained. First, the sequence of ten odd-N isotopes is too long to be associated with the $h_{11/2}$ orbital alone; second, the slope corresponds to an effective charge that would be unusually large for neutrons. The data is currently understood as simultaneous filling off several neutron orbitals inducing proton-core polarization [14]. Shell-model calculations, for instance those presented in Fig. 3 (a), do not reproduce the data quantitatively. The code OXBASH [15] is used with an effective interaction designated as “snet” and effective charges $e_\mathrm{p} = 1.35e$ and $e_\mathrm{n} = 0.35e$. The empty squares correspond to a calculation where the two proton holes in cadmium are fixed on the $p_{1/2}$ orbital. In this case protons occupy only full orbitals and have no contribution to the quadrupole moment. In this manner a linear trend is indeed observed for $^{119\text{-}129}$Cd. By allowing in addition migration of the proton holes to the $g_{9/2}$ orbital the magnitude of the quadrupole moments, shown with filled squares in Fig. 3 (a), is improved. This is a clear manifestation of the proton-core polarization. While the shell theory is incorporating the latest experimental data there is an elegant way of approaching the problem experimentally. Tin has a closed proton shell which should make all the isotopes rigid against proton excitations, thus reducing the possibility of polarization. Currently one can not obtain a single-particle quadrupole moment for tin from the existing data presented in Fig. 3 (b). The slope is already well defined, but the value extracted via Eq. 1 would depend, as discussed in Ref. [14], on the unknown number of quadrupole moments sitting on that trend.

Finally, experiments on magic-plus-minus-one-nucleon cases, such as ^{99}Cd, ^{131}Cd, and ^{133}Sn would provide theory with observables from pure wave functions, that is if no deterioration of the corresponding shell gaps is detected. In either case invaluable contribution would be made to the theoretical modeling of the region, as properties of in-shell nuclei are often difficult to interpret due to contributions from multiple shells.

3 Beam-time estimate

In this proposal we stated 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.

Indeed, assuming a modest efficiency for fluorescence detection of 10^{-4} photons/ion, a laser background of 2 kHz, and 30 points in a spectrum, the fluorescence signal from a continuous beam of 10^5 ions/s would exceed the background noise by three standard deviations after 2 hours. Odd isotopes, on the other hand, have weaker transitions and fit in a much larger scanning range, therefore the intensity required to satisfy the $3 \times \sigma$ condition is an order of magnitude higher. Correspondingly, the limit for fluorescence detection of continuous beams is 10^5 ions/μC for even-even isotopes and 10^6 ions/μC for isotopes with hyperfine structure. These numbers represent an intermediate step in the calculation, as additional factors would still apply according to the specifics of a measurement. It has to be noted that the unit (ions/s) for the ion-beam current has been replaced by (ions/μC). This substitution is critical. The maximum proton intensity available from the proton synchrotron booster is 3×10^{13} protons per bunch once every 1.2 s, being equivalent to 4 μC/s. ISOLDE is typically granted half of the proton pulses in a supercycle due to sharing with other CERN experiments. In addition we make a very conservative assumption of using only half of the proton intensity. Accordingly, the proton beam is taken as 1 μC/s, which justifies the substitution above. When bunched beams from the ISOLDE radio-frequency Paul trap are used the optical detection is operated in coincidence mode resulting in a background reduction with a factor of T_2/T_1, where T_1 is the trap-accumulation time and T_2 is the temporal bunch width. Typical values are $T_1 = 100$ ms and $T_2 = 10$ μs corresponding to a signal-to-noise reduction, and therefore, an increase of sensitivity by a factor of $\sqrt{T_2/T_1} = 10^2$. This finally justifies the feasibility limits stated in our proposal, and in the beginning of this section.

The yields of all isotopes proposed here are published in a recognized peer-reviewed journal. Figures 5 and 6 in Ref. [16] clearly show production of $^{104\text{-}136}$Sn well above the established detection limit, even for those isotopes measured with protons impinging on a “neutron converter”. This confirms the feasibility of the proposed measurements on tin. In the case of cadmium we have determined an efficiency for fluorescence detection in the 215-nm ionic transition as high as one photon in five hundred ions (2×10^{-3}) [14]. This is a twentyfold improvement with respect to the considerations above. Consequently the required production for an odd cadmium isotope drops to just 5×10^2 ions/μC. The reported yields are: 4.5×10^2 ions/μC for ^{99}Cd and 1.0×10^3 ions/μC for ^{131}Cd [17], both at the limit of detection.

The neutron-rich beams will have a well-know contribution from surface-ionized spallation products, mostly caesium. Laser spectroscopy is selective as laser excitations can only occur in the element of interest. In this respect the isobaric contamination could be a concern only if it causes a space-charge effect in the ISOLDE buncher. Thorough examination of the device has shown an empirical limit of several pA (several times 10^7 ions/s) before the space charge has any influence on the beam energy. This is important only for isotope-shift measurement and mostly for light elements due to their small field shifts. Tin and cadmium are not as susceptible to this effect and therefore could tolerate higher levels of contamination. The neutron-rich tin beams will be purified with the use of a neutron converter. In this we consider the existing design which provides caesium suppression of about two orders of magnitude [18, 19]. Further improvement of the tin-to-caesium ratio will be achieved by exploring the difference in their release times. The total beam current will be controlled to within the buncher requirements with the aperture of the slits. The ^{131}Cd beam will be purified with a quartz transfer line [16]. The use of a neutron converter is undesirable, unless a similar yield could be achieved with the next-generation converter targets at ISOLDE. Measurements with proton-irradiated quartz-line target UC338 showed suppression of ^{130}Cs down to 9.3×10^5 ions/μC [20]. Simmilar figure is to be expected for ^{131}Cs. Further means of reducing surface-ionized contaminants, such as “micro gating” with the repetition rate of the laser ion source or a LIST-type target are not considered in this proposal. There is no particular concern about beam purity for any of the neutron-deficient cases.

Collinear laser spectroscopy is not a typical counting experiment since most of the beam time is dedicated to preparation of separate measurements as well as multiple calibrations. This proposal aims at recording data over 36 isotopes, each requiring three independent measurements, each of which measurements is to be calibrated. This procedure alone requires more than 200 mass selections via the high-resolution separator, 15 min each. This is equivalent to about 50 hours or 6 shifts of beam time, which does not include standard procedures on line-voltage changes, laser adjustments, etc. The most transparent way to look at the present beam-time request is probably to look at it in reversed order. The neutron-rich tin and cadmium can not be investigated from the same target since the cadmium must use a quartz transfer line and the tin must not. The neutron-rich and the neutron-deficient isotopes obviously require different target materials and ^{99}Cd can not be combined with the neutron-deficient tin isotopes, because it requires a dedicated experiment. As a result this proposal requires the use of no less than four different target units. Consequently the beam time is requested in four independent runs, each essentially constrained by the target lifetime. Below the specific requirements of each run are listed. The experiments on neutron-rich isotopes are understandably longer. In the case of tin it is simply due to the larger amount of accessible neutron-rich isotopes. In the case of ^{131}Cd, even though the yield is larger than the one of ^{99}Cd one has to account for constraints set by the beam contamination. The same argument is partly valid also for the neutron-rich tin isotopes. This justifies the difference of two shifts between the separate runs. One shift of stable beam is asked before each run as a standard procedure of calibration measurements over the sequence of stable isotopes. Two additional shifts are requested for off-line characterization of the 215-nm transition in the ion of tin. The latter does not require RILIS as a plasma ion source could be used instead.

• 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 in the ion of tin;

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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