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

IS549: Coulomb Excitation of Neutron-rich ^{134,136}Sn isotopes

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Abstract: We propose to study excited states in the isotopes ^{134,136}Sn by γ-ray spectroscopy following "safe" Coulomb excitation. The experiment aims to investigate the evolution of quadrupole collectivity beyond the magic shell closure at $N = 82$ by the determination of $B(E2)$ values, electric quadrupole moments Q_2 and g factors. Recent shell-model calculations using realistic interactions predict possible enhanced collectivity in neutron-rich regions. Evidence for this could be obtained by this experiment.

Remaining shifts: [30] shifts
Installation: [MINIBALL + CD or C-REX]

1 Motivation, experimental setup/technique

The region around the doubly-magic nucleus ^{132}Sn is the focus of many efforts in both experimental and theoretical nuclear physics. Since the astrophysical r process is expected to pass through this region, the understanding of the nuclear structure has also an impact on the description of the $A \approx 130$ peak in the solar element abundances[1].
The Sn isotopes between ^{102}Sn and ^{130}Sn are almost perfect textbook examples of nuclei described by a seniority scheme. The excitation energy of the first 2^+ state is nearly constant at around 1200 keV and the $B(E2; 0^+_{\mathrm{gs}} \to 2^+)$ values show a parabolic behaviour peaking at mid-shell. However, starting around mid-shell from ^{114}Sn for the neutron-deficient isotopes, an enhancement of quadrupole collectivity has been observed, see for example [3, 4, 5]. However, there is still a spread of the experimental values. The most recent theoretical study appplying the Monte Carlo shell model is capable to reproduce the trend [2]. The GT strength observed in the β-decay of ^{100}Sn has proven the simultaneous robustness of both shell closures at $Z = 50$ and $N = 50$ in this doubly-magic nucleus [6]. For doubly magic ^{132}Sn a recent experiment performed at HIE-ISOLDE with the MINI-BALL & C-REX set-up has revealed an enhanced $E2$ and $E3$ strength with the first being well in agreement with theory predictions [9].
Interestingly, the picture changes dramatically going beyond $N = 82$. The excitation energy of the first 2^+ state in ^{134}Sn is only at 725.6 keV. In contrast, the measured $B(E2; 0^+_{\mathrm{gs}} \to 2^+)$ value of 0.029(5) $e^2\mathrm{b}^2$ value is very similar to the value for the two-hole nucleus ^{130}Sn [7]. However, the value has a large error as it has been determined from a γ-ray spectrum obtained with low-resolution $\mathrm{BaF_2}$ detectors.
Beyond, only the excitation energies of the 6^+ isomer and the 4^+ and 2^+ states below are known for ^{134,136,138}Sn from isomer decay spectroscopy [8]. The excitation energies of the first 2^+ states stay rather constant with 688 keV and 715 keV for ^{136,138}Sn, respectively[2]. Above this isomer, only for ^{134}Sn a (8^+) state is known from prompt spectroscopy of fission fragments [10]. No candidates for 3^- octupole states are known beyond ^{132}Sn [19]. Various approaches have been used to generate shell-model interactions capable of predic-iting the behavior of neutron-rich nuclei beyond $N = 82$ using either empirical approaches (e.g. SMPN) [15] or realistic free nucleon-nucleon potentials (e.g. CD-Bonn), renormal-ized by either G-matrix (e.g. CWG) [16] or $V_{low\,k}$ methods [14]. For Sn isotopes, the calculations with empirical interactions predicts even a new shell closure at $N = 90$ as the $\nu f_{7/2}$ orbital is filled, whereas the calculations with realistic interactions do not find such an effect. The $\nu f_{7/2}$ orbit being filled beyond $N = 82$ has an interesting analogy with the Ca isotopic chain where a $\nu f_{7/2}$ orbital is filled between $N = 20$ and $N = 28$. There was the long-standing problem that realistic interactions were not able to reproduce the shell closure at $N = 28$. This has been resolved very recently by including three-body forces [17]. Indeed, including three-body forces a shell closure at $N = 90$ occuring in ^{140}Sn is predicted also by calculations based on realistic interactions (CWG3M) [18].

[1] In 2017, for the first time observations confirmed a binary neutron star merger as an astrophysical site of the r-process with the light curves as indicator for the composition of isotopes produced and their decay [1].

[2] The observed γ-rays had all the same intensity and were ordered into a level scheme as suggested by theory

Despite the fact that the $B(E2; 0^+_{\rm gs} \rightarrow 2^+)$ value for ^{134}Sn is nicely reproduced, the predictions for ^{136}Sn, and beyond, differ considerably. Whereas the calculations with empirical interactions predicts even a new shell closure at $N = 90$ as the $\nu f_{7/2}$ orbital is filled, the calculations with realistic interactions do not find such an effect. Already for ^{136}Sn the predictions for the $E(2^+)$ excitation energies differ by 150 keV and for the $B(E2; 0^+_{\rm gs} \rightarrow 2^+)$ value by nearly 40%.

The $\nu f_{7/2}$ orbit, present at low energies in the Sn nuclei beyond $N = 82$ has an interesting analogy with the situation in the Ca isotopic chain where a $\nu f_{7/2}$ orbital is filled between $N = 20$ and $N = 28$. There was the long-standing problem that realistic interactions were not able to reproduce the shell closure at $N = 28$. This has been resolved recently by including three-body forces [17]. Indeed, including three-body forces a shell closure at $N = 90$ occuring in ^{140}Sn is predicted also by calculations based on realistic interactions (CWG3M) [18].

The Sn isotopes around ^{132}Sn have been also discussed in the framework of a reduced neutron pairing gap above $N = 82$. However, it has been found that, as expected, the $B(E2)$ value is rather insensitive, whereas the low excitation energy is better reproduced in QRPA calculations assuming a weaker neutron pairing [24]. The new $B(E2)$ value for ^{132}Sn [9] is by factor of about 2 larger than the predictions, whereas the $B(E2)$ value for ^{134}Sn is reproduced well.

Beyond these specific measurements, knowledge of the structure of the Sn isotopes is particularly important to test the neutron-neutron part of shell-model interactions as proton-proton and proton-neutron terms do not contribute at low energies and, therefore, low-lying states have a pure neutronic character. The results of the proposed experiment will aid the understanding of the evolution of neutron-neutron two-body matrix elements in nuclei with large neutron excesses.

To summarise the predictions for the $B(E2)$ values (details are given in the original proposal [20]): for the $B(E2, 0^+ \rightarrow 2^+)$ values around 0.03 e^2b^2 and 0.045-0.062 e^2b^2 for ^{134,136}Sn, respectively, are predicted. The most recent Monte Carlo shell model calculation predicts a value around 0.04 e^2b^2, hence a considerably larger value, and 0.06 e^2b^2 for ^{134,136}Sn, respectively [2].

The method is safe Coulomb excitation with γ-ray spectroscopy applying MINIBALL [21] and a coincident particle detection by the C-REX Si detector array or a single CD detector in forward direction. C-REX is version of T-REX [22], optimised to perform Coulomb excitation experiments with a large angular coverage. It consists of a forward CD[3] ($22^\circ < \vartheta_{Lab} < 60^\circ$), and in backward direction a barrel detector and a backward CD ($105^\circ < \vartheta_{Lab} < 172^\circ$).

Since we expect maximum only two-step excitations up to the 4^+ state (the isomeric 6^+ state and states above are not reachable by Coulomb excitation), also a single CD detector in forward direction would be sufficient. But the analysis of the reorientation effect enabling to extract the diagonal matrix elements would clearly profit from a larger angular coverage.

The experiment profits from the higher beam energy available at HIE-ISOLDE of 4.4 MeV/u which allows for the use of a high-Z target.

[3] The distance between forward CD and target is adjustable if more forward coverage is desired.

The analysis of the excitation probabilities will be done relatively to the target excitation. We propose to use a ^{206}Pb target. The decay of the only excited state ($E(2^+) = 803$ keV) is well separated from the expected γ-rays. The recoiling target nuclei are also kinematically separated from the scattered projectiles.
From our previous experience with A-Sn beams produced as ^{A}Sn^{34}S^{+1} molecular ions, we expect as major contaminants the respective A-isobars, mainly ^{A}Sb, and isotopes with $A + 34$, in particular $^{A+34}$Yb [9, 26]. The isotope ^{134}Sn ($T_{1/2} = 1.05$ s [19]) will decay to a small amount, about 10 %, similar to ^{142}Xe (1.23 s) measured 2016 [25], inside the EBIS adding to the contamination. The beam composition will be determined applying the several techniques we established [9, 25, 26].
We propose to measure the $B(E2; 0^+_{\mathrm{gs}} \to 2^+)$ values for the neutron-rich isotopes ^{134}Sn. Currently, a measurement of ^{136}Sn seems unrealistic (see below). Therefore, we concentrate on the isotope ^{134}Sn for which the precision of the $B(E2; 0^+_{\mathrm{gs}} \to 2^+)$ value will be improved. In addition, the $B(E2; 2^+ \to 4^+)$ will be measured for the first time. Also electric quadrupole moments Q_2 can be extracted from the experimental data. For short-lived states, this quantity is only accessible by safe Coulomb excitation via the reorientation effect. The large statistics will also allow for a determination of the g factors applying the RIV method [11, 12].

2 Status report

The experiment was not scheduled so far.
The amount of information on the evolution of collectivity in this region accessible by our approach cannot be obtained by other methods.
Lifetime measurements do not allow for determination of diagonal matrix elements. However, the Sn isotopes are anyway only very weakly populated in neutron-induced or spontaneous fission of actinides. Also the statistics obtainable in isomer decay spectroscopy, see [8], are by far not sufficient for a fast-timing analysis.
On the other hand, Coulomb excitation at intermediate beam energies turned out to be more difficult to be analysed than previously done, e.g. demonstrated for ^{136}Te at RIKEN [13]. But more important is the fact that excitations beyond the first 2^+ state are very suppressed.
Accepted isotopes: ^{134,136}Sn
Performed studies: 0 shifts

3 Future plans

Future plans with available shifts:

(i) Envisaged measurements, beam energy, and requested isotopes

Considering the lower available yields compared to the original proposal we do not think that a reasonable measurement of ^{136}Sn is possible at the moment. If higher yields, e.g. due to the upgrade of the PS-Booster to 2 GeV, are available, we will come back to the INTC with an Addendum. Therefore, we ask to dedicate all approved shifts to a measurement of ^{134}Sn in order to obtain the electromagnetic matrix elements within the errors given in the original proposal. In the view of the new predictions from theory mentioned above [2], already the measurement of the $B(E2, 0^+_{gs} \rightarrow 2^+)$ value within the intended precision will have a considerable impact on the understanding of the nuclear structure of Sn isotopes beyond $N = 82$. The additional quantities, like $B(E2, 2^+ \rightarrow 4^+)$, quadrupole moments, and g factors ... or the possible observation of a candidate for the first 3^- octupole state, will add to a comprehensive understanding.

We ask to use all approved 30 shifts for the study of ^{134}Sn.

(ii) Have these studies been performed in the meantime by another group?
No. Beams of neutron-rich Sn isotopes at this energy are not available anywhere else.

(iii) Number of shifts (based on newest yields and latest REXEBIS and REXtrap efficiencies) required for each isotope

The Sn isotopes of interest are produced using a standard UC_x/graphite target irradiated with the proton beam from the PS Booster. The VADIS ion source will be used, see e.g. [26].
In the original proposal, expected yields of $10^6/\mu$C and $2{\cdot}10^4/\mu$C for ^{134,136}Sn, respectively, as recommended by the ISOLDE target group at this time were used [20, 27]. Newer yield estimates, which are consistent with the beam intensity obtained 2016 for ^{132}Sn [9], are lower by a factor of 10 [26]. During the run of IS654 in 2018 the conditions were much worse concerning intensity and stability [26]. We assume that the conditions achieved in 2016 can be reproduced and a beam intensity of about 10^4/s for ^{134}Sn can be obtained (as requested also for IS654 [26]).

Isotope	Yield (/μC)	Target - ion source	Shifts (8h)
^{134}Sn	10^5		30

By using a thicker target, 3-4 mg/cm^2, than in the original proposal the statistics can be increased (has been used 2016 in IS551 [9] and IS548 [25]). Together with the increase of beamtime from 6 shifts (original proposal) to 30 shifts the intended statistics resulting in the precision as discussed in the proposal can be achieved.
Total remaining shifts: 30

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