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

IS654: First spectroscopy of the the r-process nucleus ^{135}Sn

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Abstract: We propose to study states in the isotope ^{135}Sn populated by a ^{134}Sn(d,p) one-neutron transfer reaction at 10 MeV/u in inverse kinematics. The experimental set-up will consist of MINIBALL and T-REX. We aim for the identification of excited states in this nucleus for the first time. Excitation energies, spin-parity assignments and spectroscopic factors extracted from the data will allow for a stringent test of predictions by state-of-the-art shell model calculations in this region.

Remaining shifts: [22] shifts
Installation: [MINIBALL + T-REX]

1 Motivation, experimental setup/technique

The understanding of doubly-magic shell closures is the benchmark for any nuclear theory. On the neutron-rich side of the nuclear chart, the region around ^{132}Sn is the focus of many efforts in both experimental and theoretical nuclear physics. Additional interest comes from nuclear astrophysics as the r-process[1] approaches ^{132}Sn from the neutron-rich $N = 82$ waiting point nuclei, and then proceeds along the $Z = 50$ isotopic chain towards more neutron-rich nuclei. Masses, β halflifes and (n,γ) rates, all directly linked to the nuclear structure of the involved isotopes, are crucial inputs for the description of the $A \approx 130$ peak in the solar element abundances [1, 2]. Extrapolation towards heavier Sn isotopes therefore requires a strong anchor point at the doubly-magic ^{132}Sn. First spectroscopy and neutron spectroscopic factors for ^{135}Sn will therefore serve as a benchmark for nuclear theory and also give important information on the direct neutron capture process.
Single-particle properties are investigated most directly by nucleon transfer reactions, e.g. (d,p), closely related to (n, γ) neutron capture, or (t,p). Main observables are the cross sections as well as the energies and the angular distributions of the outgoing protons which allow for the determination of excitation energies, transferred angular momenta and spectroscopic factors. For heavy beams around ^{132}Sn well-pronounced angular distributions require beam energies of 7.5 or 10 MeV/u as they became available at HIE-ISOLDE in 2018.
Transfer reactions in this region have been pioneered at Oak Ridge National Laboratory some years ago [4]. The reaction ^{132}Sn(d,p) has been investigated at a beam energy of 4.77 MeV/u, but detecting only the emitted protons. The ground state and three excited states with excitation energies of 854 keV, 1363 keV, and 2005 keV were populated. The energy resolution was just sufficient to resolve these states. Although the angular distributions of the emitted protons were rather smooth at this low beam energy, for the two lowest states an assignment of the transferred orbital angular momentum to be $\Delta\ell = 1$ or 3 was possible.
For our isotope of interest, ^{135}Sn, experimentally no excited state is known so far [5]. Details of our shell model calculations, energies and spectroscopic factors, can be found in the original proposal [8].
We will apply the method of particle spectroscopy in combination with γ-ray spectroscopy following a one-neutron (d,p) transfer reaction with a CD_2 target. The set-up will consist of MINIBALL [6] and T-REX [7].

2 Status report

A first attempt to perform this experiment was done in autumn 2018 at an beam energy of 7.3 MeV/u, the highest beam energy available for this run. In the presentation of the proposal to the INTC, the pro's and con's of using beams at 7.5 MeV/u and 10 MeV/u have been discussed. For the first time since 2011, with great effort the full T-REX

[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 [3].

detector set-up was mounted.
As proposed a ^{134}Sn^{34}S^{+} molecular beam was produced. The beam intensity of 10^4/s ^{134}Sn at the MINIBALL target station required in the proposal was not reached. The maximum intensity was $2.7 \cdot 10^3$/s. This number has been deduced from the intensity of the 872 keV transition in ^{134}Sb following the β-decay of ^{134}Sn nuclei stopped within MINIBALL. Note: the branching ratio of 6(3)% to excited states in ^{134}Sb and the branching ratio to β-delayed neutron emission of 17(13)% populating ^{133}Sb are only poorly known [5], for the given intensity an error of larger 50% has to be considered.
The beam delivered contained the expected contaminations of $A = 134$ isobars (identified by the *delayed characteristic γ-rays* following their β-decay when the beam was stopped inside MINIBALL) and ^{168}Yb (identified by *prompt characteristic γ-rays* following inelastic scattering on the target) as well as an unidentified contaminant with mass $A \approx 156$ (no additional γ-ray observed; this contaminant was detected only in the *measurements with the IC-Si telescope* in the beam dump). Since the methods are different and cannot be operated in parallel, we have not deduced a quantitative composition of the beam.
However, over the course of few hours, the ^{134}Sn intensity decreased to below our detection limit which we estimate to be in the order of a couple γ-rays of 872 keV per minute (depends on the background due to the accumulated activity from the daughter products and the beam contaminants).
Optimisation of the target heating and sulphur oven or changing the settings of the trap, EBIS, focussing or separators did not improve the situation. The absolute intensity of the beam contamination could be restored to the value achieved in the beginning of the beam tuning, but the purity for ^{134}Sn at this time was already 0. Several trips of "XLH1 Cav4" prevented a stable operation.
The beam was changed to mass $A = 132$ hoping to take some data and improve the situation for the ^{132}Sn(d,p) reaction compared to what has been done at Oak Ridge at lower beam energy and without γ-ray detection [4]. Compared to the $2.4 \cdot 10^5$/s obtained previously 2016 in experiment IS551 [9], only a maximum intensity of about $2.1 \cdot 10^4$/s ^{132}Sn could be obtained. This number was deduced from the intensity of the 993 keV γ-line in ^{132}Sb following the β-decay of ^{132}Sn. The branching ratio is known with an error of 5% and we estimate that the given intensity is reliable within an error of 15%, dominated by the error for the absolute efficiency of around 10% for MINIBALL. However, the primary target broke soon after the data taking started and not much statistics could be collected for the ^{132}Sn(d,p) reaction.
The experiment continued with stable ^{132}Xe beam which allowed us to prove the feasibility of transfer reactions with the MINIBALL & T-REX set-up with heavy beams at HIE-ISOLDE energies. Fig. 1 shows the reconstructed excitation energy spectra for protons detected in the backward barrel. For the simulation, FRESCO calculations have been performed using the known excitation energies [10]. However, the low statistics does not allow to obtain a coincident γ-ray spectrum.

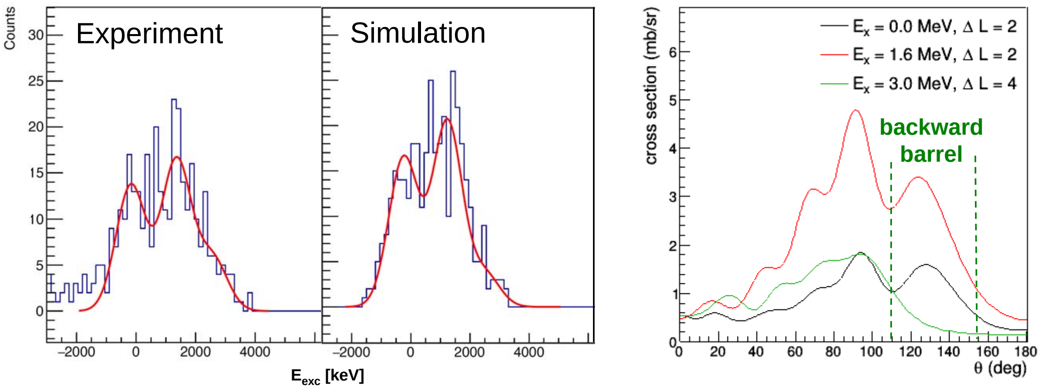

Figure 1: *Reconstructed excitation energy spectrum from the* ^{132}*Xe(d,p) reaction at 7.3 MeV/u: experiment (left) and simulation (centre). The red curve shows a fit with three peaks to the data. The right part of the figure shows the calculated angular distribution of the protons. The different transferred angular momenta can be distinguished even in the backward barrel only* ($110° < \vartheta_{Lab} < 155°$)*.*

It has to be mentioned that the yield of delta electrons for such a high beam energy and heavy beam was quite high. In particular, the barrel detectors of T-REX had problems at an beam intensity of 10^4/s (the highest available in this run). For DSSSDs (CD detectors) with their high segmentation the delta electrons were no problem. Although the problem could not be studied in detail, e.g. with HV on the target and/or thicker protection foils in front of the detectors, because of the early failure of the primary target, this problem lead to the design of a new T-REX consisting of DSSSDs only. A first in-beam run of a prototype detector will be performed in early July 2019 at the MLL tandem laboratory in München. After LS2 this new T-REX will be available for experiments at HIE-ISOLDE. Meanwhile, with the ISS (ISOLDE solenoidal spectrometer) a second experimental set-up dedicated to the study of nucleon-transfer reactions became operational in 2018. The achievable energy resolution of about 100 keV is better than with T-REX, but still much worse compared to gamma-ray spectroscopy with MINIBALL. However, the drop in statistics requiring an additional gamma-ray has to be taken into account. In particular in nuclei with odd neutron and/or proton number the level density is higher which requires the higher resolution offered by MINIBALL. This is not plain theory ... already in the commissioning run of ISS the doublet in ^{29}Mg at 3223.7 keV and 3227.5 keV (no or only tentative spin-parity assignment) was populated in ^{28}Mg(d,p) and could not be resolved [14]. Although an energy resolution for Doppler corrected γ-rays in the order of 4 keV at 3 MeV is out of reach also for MINIBALL, the very different decay patterns of the two states would have enabled an analysis of the angular distributions of the protons populating the two states.
As the level scheme of ^{135}Sn remains unknown, we would like to profit from the higher resolution offered by coincident gamma-ray spectroscopy. In addition, as the angular distribution only allows for conclusions on the orbital momentum transfer $\Delta\ell$, the decay pattern can help in doing spin-parity assignments.

To our knowledge, no new published data on ^{135}Sn exist. It is difficult to approach ^{135}Sn by other techniques. The cross section for the mother isotope ^{135}In produced in fragmentation e.g. at RIKEN is similar to ^{138}Sn [11], the heaviest Sn isotope studied in isomer-decay spectroscopy so far [12]. From systematics for ^{135}In $I^{\pi}_{\rm gs} = 9/2^{+}$ and a $Q(\beta) \approx 14$ MeV are expected [13], hence rather high-lying neutron-unbound states in ^{135}Sn instead of low-lying negative-parity states will be populated. This region is also very weakly populated in neutron-induced fission of actinides (EXILL or LICORNE) as well as spontaneous fission of e.g. ^{252}Cf which does not allow doing prompt spectroscopy. Other direct reaction types at much higher beam energies like knockout or (p,pX), all nucleon-removal reactions, are complementary because they populate hole-states. Such experiments would be possible, e.g. at RIKEN. Anyway, the high level density in this odd-even nucleus would require a high-resolution detector array capable to deal with the large Doppler broadening.

Accepted isotopes: ^{134}Sn
Performed studies: 2 shifts

3 Future plans

Future plans with available shifts:

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

As described, we plan to perform the reaction d(^{134}Sn,^{135}Sn)p at 7.5-10 MeV/u. As discussed in the presentation of the proposal, the lower energy results in a slightly higher cross section whereas the higher energy results in higher energies of the protons making it easier to separate them from the background. The angular distribution are well pronounced for these energies allowing for a determination of the transferred orbital angular momentum $\Delta\ell$.

(ii) Have these studies been performed in the meantime by another group?

No. Sn beams at this energy are not available anywhere else. Also, no new experimental results for ^{135}Sn obtained by any other method has been published.

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

From the estimated yield of $10^5/\mu$C we estimate a beam intensity on target of about 10^4/s [8]. The yield estimate is already an order of magnitude lower compared to the more optimistic number of $10^6/\mu$C recommended to be used in 2012 [15]. For the estimate of the beam intensity has been assumed that the efficiency of HIE-ISOLDE is comparable to REX-ISOLDE. Various tests have shown that the efficiency of the HIE-ISOLDE facility is thanks to the efforts of the HIE-ISOLDE team very good. Taking into account that also for ^{132}Sn the beam intensity in 2018 was an order of magnitude smaller compared to 2016 [9], under the same conditions as 2016 the required intensity of 10^4/s for ^{134}Sn seems to be achievable.

Isotope	Yield (/μC)	Target - ion source	Shifts (8h)
^{134}Sn	10^5	VADIS	22

Total remaining shifts: 22

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