EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Total absorption spectroscopy of neutron-rich indium isotopes beyond N=82

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Abstract The goal of the proposal is to study β-decay properties of nuclei around double-magic ^{132}Sn, which is an ideal playground to explore the single particle energies and the two-body matrix elements of the residual interaction. The properties of the nuclei around double-magic ^{132}Sn are also relevant for the study of astrophysical rapid neutron capture process (r-process). Recently, neutron-γ-ray competition in the decay of neutron-unbound states populated in β decay of $^{133-134}$In was observed. The large Q-values along the isotopic chain of In isotopes from 132 to 134 offer an excellent opportunity to probe low-lying collective modes in the Sn daughter nuclei, where pygmy dipole resonances have been evidenced around 10 MeV at fragmentation facilities. Such phenomena are believed to have vast consequences for r-process modelling. We propose, in particular, to investigate the β decay of the $^{132-134}$In nuclei by means of the LUCRECIA total absorption spectrometer.

Requested shifts: [22] shifts, (split into [1] runs over [1] years)

1 Introduction

The goal of this proposal is to investigate the β-decay properties of neutron-rich indium isotopes around the double-magic ^{132}Sn by means of the LUCRECIA total absorption spectrometer (TAS). This region of the chart of nuclei offers the unique possibility to look at nuclear properties of exotic nuclei beyond the N=82 shell closure. The study of ^{133,134}In isotopes, which decay to the one-neutron particle ^{133}Sn and the two-neutron particle ^{134}Sn nuclei represents an ideal case to explore the single particle energies and the two-body matrix elements of the residual interaction. These nuclei are rather simple systems, which renders them ideal cases for testing the predictive power of theoretical calculations far from stability, in the vicinity of ^{132}Sn. Despite their simplicity, theoretical calculations which include core excitations predict a rich spectrum of excited states, many of which can be populated in β decay [1]. The combination of such a rich spectrum with the large Q-values available for β decay (see Table 1) allows to expect several high-energy γ-ray transitions from excited states above the neutron-separation energy. Several cases have been reported in which γ-ray transitions successfully compete with neutron emission, in particular ^{133}Sn [2, 3] and ^{134}Sn [4].

The neutron-γ-ray competition in the decay of neutron-unbound states is believed to have important consequences for the astrophysical r-process around the double-magic

Table 1: The β-decay energy windows (Q_β) of ^{132}In, ^{133}In and ^{134}In [5].

^{132}In	^{133}In	^{134}In
14.14(6) MeV	13.41(20) MeV	14.8(3) MeV

^{132}Sn, since it was indicated that it may affect its modelling [6, 7]. So far, all theoretical calculations have assumed that neutron emission dominates the decay whenever it is energetically possible.

These recent observations suggest that the competition between γ-ray and neutron emission requires a more thorough investigation. In this respect, the effectiveness of using TAS to study the neutron-γ-ray competition phenomenon has been proven in several experiments [8, 9]. In the case of the neutron-rich indium isotopes, the use of total absorption spectroscopy is of particular relevance given the high energy of the γ-ray transitions involved, which would be difficult to detect with HPGe detectors.

The β decay could also populate low-lying collective modes such as pygmy dipole resonances (PDR), which may de-excite through high energy γ-rays carrying the collectivity of the state (direct decay). The excitation of PDR through the Gamow-Teller operator was predicted theoretically in [10, 11], showing that β-decay excites complementary components of the collective modes with respect to nuclear or electromagnetic reactions. These modes, besides their fundamental interest for nuclear structure, influence greatly the r-process calculations in the mass region A$\sim$130, N$\sim$82 and N$\sim$126 as was evidenced by Goriely in 1998 [12]. However, large uncertainties affect the predictions of PDR characteristics (Electric dipole strength function, excitation energy,...). The β-decay studies of low-lying collective modes in exotic nuclei may allow one to overcome the limited beam intensities, which prevent the study of the evolution of these modes in the most exotic nuclei with reactions.

Recently, the β decays of ^{133}In and ^{134}In have been measured at the IDS both with high-resolution γ-ray detectors [3, 4, 13], as well as by means of the neutron time-of-flight technique [14]. Total absorption spectroscopy are therefore mandatory studies to find the answers to the still open questions and to quantify better previous observations. Thanks to the high efficiency of the LUCRECIA crystal and its geometry, covering almost a 4π solid angle surrounding the radioactive samples, the spectrometer has almost 100% efficiency for the γ-ray cascades produced after the decay. This is necessary to avoid the so called Pandemonium effect [15] and thus to be sensitive to weak β feedings at high excitation energy. As demonstrated in a number of cases (see e.g. [16], [17]), this is the best method to deduce the B(GT). Moreover, the high resolution data are often insufficient to correctly assign all γ-ray transitions to levels. Consequently the β-feeding is called 'apparent β-feeding'. With our TAS data we will be able to obtain the 'real β-feeding'. Still, the analysis of the TAS data relies on having sufficient knowledge of the decay scheme [18]. Fortunatelly, the high-resolution data needed for these analyses are available [3, 4, 13]. All measurements were performed at the ISOLDE Decay Station.

Total absorption spectroscopy of such short-lived nuclei will require the unique combination of high beam intensities for the exotic ^{132}In, ^{133}In and ^{134}In isotopes, beam purity and in-beam measurement during implantation of the radiation on the tape, which is offered by the LUCRECIA spectrometer in

combination with the use of RILIS at ISOLDE.

2 Physics cases

The decay of ^{134}In is particularly interesting. The daughter nucleus ^{134}Sn is a rather simple system with its magic proton number Z=50 and only 2 neutrons above the closed N=82 shell, see Fig 1. Understanding such a system is crucial in order to be able to make predictions about the structure of the nuclei further away from magicity. In addition, this simple system is still very poorly studied, with only 4 excited states in ^{134}Sn reported in the literature so far [19]. The β decay of ^{134}In was investigated for the first time in a measurement performed in the mid 1990s, but at that time only the population of states in the β-delayed neutron daughter ^{133}Sn was observed [20]. Large-scale shell-model calculations with core excitations predict the existence of several highly excited states in the ^{134}Sn nucleus [1]. Some light on the structure of ^{134}Sn was shed by the latest IDS experiment, which yielded the first observation of excited states in ^{134}Sn populated in β decay [4]. However, more excited states are expected and have still to be observed. Their experimental identification is essential in order to validate effective nucleon-nucleon interactions employed in these models and to investigate states populated via Gamow-Teller transitions, in particular the $\nu g_{7/2} \rightarrow \pi g_{9/2}$ transition.

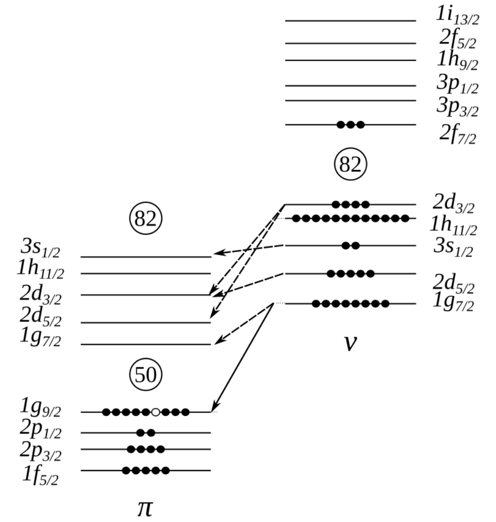

Figure 1: Single-particle orbitals relevant for the nuclei around ^{132}Sn. The dots represent the ground-state configuration for ^{134}In. Arrows represent Gamow-Teller transitions resulting in population of neutron-unbound states in Sn nuclei.

Another, extremely important aspect of the β decay study of ^{134}In is the possibility to investigate single-particle levels above N=82 in ^{133}Sn by looking at the delayed-neutron decay-branch. Single-particle levels above N=82 were first investigated in the decay of ^{134}In [20], and then confirmed in the neutron-transfer reactions ^{132}Sn(d,p)^{133}Sn [21] and one-neutron knockout from a ^{134}Sn beam [2]. The neutron single-particle level $\nu i\frac{13}{2}$, which is expected at an excitation energy of about 2.5 MeV [22], has not yet been observed experimentally. The β-decay study of ^{134}In with total absorption spectroscopy is a very promising strategy for identifying this last experimentally-unknown neutron single-particle level in the region.

In the β decay of $^{133-134}$In, Gamow-Teller transitions from neutron single-particle states inside the N=82 core to the empty proton orbitals above Z=50 will populate excited states located above the neutron separation energy [14], as shown in Fig 1. Expectations that all levels above the neutron separation energy in tin isotopes will de-excite by the emission of a β-delayed neutron are not necessarily met. In fact, recent IDS measurements showed γ-ray transitions from levels located at energies exceeding the S$_n$ by 1-to-3.5 MeV [3], a clear sign of the existence of neutron-γ competition. For ^{133}Sn this phenomenon was observed first at RIKEN in one-neutron knockout from ^{134}Sn [2], later confirmed at IDS in the β-decay study of ^{133}In [3], and subsequently also in ^{134}In decay [4]. The investigation of the β decay of ^{132}In, ^{133}In and ^{134}In, with their large energy windows for population of neutron-unbound levels, by means of a high-efficiency detection system, will provide an ideal testing ground to probe the capability of γ-ray emission to compete with neutron emission well above the neutron-separation energy.

The study of the evolution of the β feeding and subsequent γ-ray emission along the isotopic chain from ^{132}In to ^{134}In feeding the corresponding Sn daughter nuclei will allow a deeper understanding of the mechanisms at play behind the high-energy γ-ray emission. Indeed several theoretical models predict an evolution of the collectivity with isospin asymmetry with a diminution of the energy centroid of the PDR and an increase of its strength [23, 24]. Experimentally, the dipole-strength distribution above the one-neutron separation energy was investigated in the unstable tin isotopes $^{129-133}$Sn including the doubly-magic nucleus ^{132}Sn [25]. While two clear peaked structures at 10 MeV identified as PDRs were observed in ^{130}Sn and ^{132}Sn, the odd isotopes ^{129,131}Sn and ^{133}Sn exhibited a sharp increase of their dipole strength between 5 and 8 MeV [26, 27], a region energetically accessible through beta-decay of the Indium isotopes. The excitation of this dipole strength through β-decay is possible when the required spin and parity conditions are fulfilled, i.e. for the decay of the $9/2^+$ isomer of ^{133}In [28]. One could also wonder if other low-lying collective modes could be accessed through the Gamow-Teller operator. An increase of the transition strength of the quadrupole pair-addition mode in Sn isotopes with A>132 has been predicted [29] with a Skyrme HFB model. Studying the β decay of the two even ^{132}In and ^{134}In isotopes could provide access to other possible low-lying collective strength.

The measurement of ^{131}In with lower delayed-neutron emission fractions and more intense beams will help the analysis of the most challenging cases ^{132}In, ^{133}In and ^{134}In.

3 Experimental set-up

As mentioned above for the proposed measurements we will use the LUCRECIA TAS. The LUCRECIA spectrometer is a single NaI crystal of cylindrical shape with dimensions 38 cm x 38 cm (diameter x length). Total efficiency for 1 MeV γ rays reaches 89% and drops only to 79% for 5 MeV γs. Full-energy absorption efficiency is 62% for 1 MeV and 44% for 5 MeV γ rays. LUCRECIA is equipped with a plastic detector for β-particle coincidence and a germanium telescope detector for the detection of low energy γ rays. See Rubio *et al.* [30] for details. A newly-developed in-vacuum tape-drive system will also be used during the experiment. Due to the short half-life of the indium isotopes under investigation, the beam will be implanted onto the tape inside the spectrometer.

For the ^{133}In and ^{134}In cases we have to consider the neutron induced background in the spectrometer. Two different approaches are considered. The first is to use the available information on the β-delayed neutron spectroscopy already available for ^{133}In [14] and planned for ^{134}In [31], see Ref. [9]. The second strategy is to use the neutron-γ-ray detection time discrimination to characterize the neutron background as explained in Ref. [32].

4 Beam-time estimate and request

Beam times were estimated based on a proton beam at 1.4 GeV and with 2 μA intensity impinging on a UC$_x$ target (lower beam intensity will be needed for A=131 and 132 because of rate limitations of LUCRECIA) equipped with a neutron converter. The RILIS ion source will be employed to selectively ionise the indium isotopes while suppressing isobaric contaminants, which is crucial for the success of the measurement. The RILIS will be operated in narrow band to study the isomeric and ground state decays selectively, when required. A 70% beam transmission to the LUCRECIA measuring station has been considered. This value takes into account transport and collimation losses.

For the beam request we use the actual count rates from previous experiments (IS610), which are compatible with the ISOLDE yield database. The total γ- and β detection efficiencies were assumed conservatively to be 80% and 40%, respectively and delayed neutron branching ratios were taken from the available literature. The number of shifts requested was calculated to have at least 1M (A=131 – 133) and 200k (A=134) events in the $\beta - \gamma$ spectrum for each β-decaying state. In Table 2 the properties of the isotopes to be investigated, the corresponding yields and beam-time requested are summarised.

Since the evaluation of daughter and granddaughter decays with the same technique is essential for data analysis, 2 shifts are requested for the measurement of the daughter activities. This is achieved by measurements with tape-system cycles adapted to nuclei with a longer half-life, and it is specifically required for A=132.

The beam-time request includes one shift to measure the β decay of ^{131}In, as shown in Table 2. Its high production rates makes it an excellent pilot beam for fine-tuning the experimental setup and in addition it allows a direct comparison with high-resolution data from ISOLDE. For the calibration of the LUCRECIA response function standard sources and an implanted ^{24}Na (T$_{1/2}$=15.0 hours) will be needed.

Table 2: Half-life T$_{1/2}$, delayed-neutron branching ratios P$_n$, production yields, expected intensity at LUCRECIA and requested shifts for each case to be investigated.

Isotope	T$_{1/2}$ ms	P$_n$ %	Yield ions/μC	Intensity at LUCRECIA ions/s	Requested shifts
^{131}In	265-328 [a]	2-12 [a]		$5\cdot10^3$	1
^{132}In	202 [13]	12 [13]	$2\cdot10^4$ [c]	$5\cdot10^3$	1
$^{133g.s.}$In	162 [3]	74 [3]	900 [c]	1300	3
^{133m}In	167 [3]	80 [3]	400 [c]	560	7
^{134}In	126 [33]	65 [5]	50 [c]	70	8

[a] P$_n$=2% for ^{131}In g.s. and (1/2+) isomer, and 12(7)% for ^{131}In (21/2+) isomer; T$_{1/2}$=265, 328 and 323 for the g.s., (1/2+) and (21/2+) isomers, respectively [34]

[c] Private communication L.M. Fraile (from analysed data)

Summary of requested shifts: 2 shifts for masses 131 and 132, 3 shifts for I$^\pi$(^{133}In)=(9/2+) g.s. decay, 7 shifts for I$^\pi$(^{133m}In)=(1/2-) decay, 8 shifts for mass 134 and 2 additional shifts for measurement of the daughter activities are requested, for a total of 22 shifts.

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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
TAS	☒ Existing	☐ To be used without any modification ☒ To be modified (The Tape Station should be updated)

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure			
Vacuum	high vacuum [10^{-6} mbar]		
Temperature	LN2 temperature [77 K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity	6.0kV (HPGe det. HV supply)		
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)	ions: $^{131-134}$In		
Beam intensity	maximum $5 \cdot 10^3$ s^{-1}		
Beam energy	60 keV		

Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
• Open source	☒		
• Sealed source	☒ [ISO standard]		
• Isotope	^{152}Eu, ^{133}Ba, ^{22}Na, ^{241}Am, ^{60}Co, ^{24}Na (open)		
• Activity	1-10 kBq		
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		

Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]