EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Beta delayed neutron emission from ^{134}In to neutron single particle states in ^{133}Sn

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Abstract

We propose to measure for the first time the delayed neutron emission in ^{132}In and the complete decay pattern of ^{134}In. The main focus of the experiment is beta delayed neutron spectroscopy, the identification of neutron unbound states in ^{132,134}Sn and their decay mechanism to states in ^{131,133}Sn. States in ^{132,134}Sn will be populated either in allowed Gamow-Teller transformations or in forbidden transformation, similarly to those observed in our recent measurement of ^{133}In decay. The systematic measurement of GT strength in both isotopes will allow us to study the effect of increasing number of neutrons in the energy and intensity of main resonances. Beta-delayed neutron emission will be observed using the ISOLDE Decay Station Neutron Detector (IDSND), recently commissioned in our measurement of ^{133}In decay.

Requested shifts: 11 shifts

Beta-delayed neutron decay – a two step process

Beta-delayed neutron emission, a two-step decay mode of very neutron-rich nuclei is a major component of reaction network models of neutron rich nuclei, such as astrophysical r-process models used to reproduce observed elemental abundance pattern [Mum16], or fission product decay networks [Kaw08] required in reactor operations and waste disposal. The key questions in the modeling of ßn-emission are: how are the nuclear states in the emitter nucleus populated in the beta decay and, how will this nucleus de excite?. To answer the first question requires the knowledge of beta transformation properties, determined by their $Q_ß$ and decay strength distribution. However, the second question is still not well understood and does not have a clear answer. A wealth of data on neutron branching ratios (P_n) exists, but unfortunately few spectroscopic data for fission fragments is available. Today, there is not enough experimental information to validate delayed neutron emission model for medium mass neutron rich precursors. Step-one, the beta-decay feeding probability, can be treated relatively reliably by nuclear structure models, such as shell model or QRPA [Mus16,Sev17,Fa13,Zhi03]. Evidence shows that the decays mediated via Gamow-Teller will populate excited states in decay daughter with very well-defined structure [Mad16] connected via GT transformation. Step-two (neutron emission) is currently treated using statistical models of the nucleus and optical models of the emission [Kaw08], based on the assumption that there are a plethora of unbound states that can be populated in the continuum of the daughter. However given how selective is the population of excited nuclear states in beta decay [Mad16], the statistical approach developed and tested for compound nucleus may be of limited use due to the strong effects of nuclear structure. Excited nuclear states populated in beta decay must have a strong overlap with, a strong "memory" of, the parent nuclear states. Predictions of the different partial branching ratios, i.e. gamma, neutron to ground state, neutron to excited state, will be compromised by the accuracy of the spectroscopic overlaps from the statistical model of the nucleus.

Recently, a series of new measurements have raised this problem to the nuclear physics community. The competition between gamma and neutron emission in beta-fed unbound states, with immense consequences for r-process modeling, was measured in neutron rich Co isotopes [Spy16]. Rasco et al. [Ras16] show an example of such analysis for the classic "pandemonium" nucleus ^{137}I. The decays of N>82 indiums are of similar type and importance as those of Co (Z=27), but the higher production rates and simplicity of nuclear structure make them much better examples to study this problem. This competition between decay channels becomes particularly critical when multi-neutron emission window opens up for the exotic r-process nuclei. In particular, the relative branching between single and two- or three neutron emission has been showed to greatly affect the modeling of the cooling phase [Mum16, Mum16b].

In another example of the complexity of the second step neutron emission mechanism, its different emission rules can be used to populate and study excited gamma-decaying states in the N-daughter nucleus not accessible in the beta-decay of the N-1 precursor. In the decay of ^{134}In, several new excited states in ^{133}Sn were identified for the first time [Hof96], confirmed to be single particle neutron excitation by (d,p) experiment [Jon10] , see Figure 1.

The ^{132}Sn region provides excellent candidates to study the neutron emission process in a systematic manner for medium mass nuclei. The proximity of doubly magic ^{132}Sn generates a favorable condition for the discrete neutron spectroscopy without the challenges of nuclear Pandemonium [Har78]. Decays of indium isotopes are characterized by very large neutron emission energy window ($Q_β$-S_n) exceeding 10 MeV, resulting in large beta delayed neutron branching ratios. The proximity of ^{132}Sn makes excited state configurations with relatively pure wave, where the shell-model approach is applicable. The continuous development of improved laser ionization schemes at ISOLDE enables the production of these isotopes with high rates, enabling spectroscopic studies of even the smaller decay channels.

Recently we proposed and performed an experiment to study the beta-delayed neutron emission from the ^{133}In precursor [Mad17]. The unique use of RILIS allowed not only a detailed study of the decay of the $9/2^+$ ground state but also $½^-$ isomer. The neutron spectrum observed in the decay of both ^{133}In emitting states showed a pattern unique to discrete transitions rather than the high density spectroscopy observed for gallium decays [mad16]. The $g_{9/2} \rightarrow g_{7/2}$ transformation dominates the decay of ^{133}In, which causes an observed strong neutron line at around 3 MeV. The width of the resonance is less than 100 keV, see Figure 2 and is much smaller than is to be expected for the pure $l=3$ emission. This is a clear indication of inhibition of the neutron emission due to the structure effects. Other weaker transitions were observed, likely forbidden transitions to states built on proton excitations across the Z=50 gap.

Gamow-Teller transitions near ^{132}Sn

Two key experiments by Madurga et al. proposed and carried out at ISOLDE identified the dominant GT transformation for ^{133}In and ^{132}Cd, see Figs. 2 and 3. The decays of these Z<50 isotopes are dominated by the single particle $g_{7/2} \rightarrow g_{9/2}$ transformation [Han00]. Because neutron $g_{7/2}$ orbital is deeply bound, the GT conversion of the neutron leaves the beta decay daughter nucleus in highly excited state, observed at 5.9 MeV in ^{133}Sn, with a very well defined particle-hole configuration. This is somewhat lower than the transition observed in ^{132}In decay at 7.2 MeV in ^{132}Sn and predictions by the shell model. The Gamow-Teller decays of ^{134}In should reflect very similar pattern as observed in ^{133}In and ^{132}Cd. The dominating beta transition will be due to the $g_{7/2} \rightarrow g_{9/2}$ transformation and should lead to a particle-hole state located around 7 MeV excitation energy in ^{134}Sn. Other GT transitions will be located ~4 MeV higher, populating proton single particle states above Z=50. One and two neutron separation energies in ^{134}Sn are S_n= 3.629 MeV and S_{2n}=6.03 MeV respectively, making all expected GT strength populate unbound states.

In the neutron spectroscopy experiment proposed here we will measure the position and strength of GT resonances. The main GT resonances will have a $\nu g_{7/2}^{-1} f_{7/2}^{+1,3}$ configuration for ^{132,134}Sn, with the $g_{7/2} \rightarrow g_{9/2}$ matrix element fully determining the decay strength. In this picture, the strength should remain the same for ^{132}In, ^{133}In, and ^{134}In. The ^{134}In measurement will allow us to verify how robust is the shell-model picture with increasing neutron number . Moreover, the beta-decay half-lives and neutron branching ratios of all Z<50 nuclei are determined by the ν-$g_{7/2}$ hole state and its decay strength. Systematic measurement of the position and strength of these resonances in the region is critical to develop beta-decay models for the entire south-eastern region of ^{132}Sn, of crucial importance for r-process calculations.

In the case of ^{132}In decay, high energy neutron resonances will provide information on beta transformations into proton single particle states above Z=50 ($g_{7/2}$, $d_{5/2}$,$d_{3/2}$,$s_{1/2}$, $h_{11/2}$) from GT transformation of the ^{132}Sn core states. The small branching ratio (Pn=6%) [Kha05] is due to the dominant decay branch $g_{7/2} \rightarrow g_{9/2}$ populates a bound excited state in ^{132}Sn at E^*=7.2 MeV. However, even this small P_n, may result from strong B(GT), only suppressed by the phase space factor. Similar states are expected to be observed in ^{134}In decay, comparably suppressed with respect of the main nu-$g_{7/2}^{-1}$ resonance.

Decay of ^{134}Sn states to single particle neutron states in ^{133}Sn

The other important question addressed in this proposal is the neutron emission mechanism populating particle states in ^{133}Sn from the beta-delayed neutron emission from ^{134}In. This is a non-trivial problem, since low excited states in ^{133}Sn are single particle excitations in the N>82 shell [Jon10] which might not be strongly present in the ^{134}In ground state wave function. We will measure neutron energies and neutron-gamma coincidences to determine the origin and probability of the population of the ground and excited states in ^{133}Sn. The GT transitions will populate neutron and two neutron unbound states in ^{134}In and neutron energies and relative neutron emission probabilities to excited states in ^{133}In will be sensitive to the nuclear structure effects. The two-neutron emission probability will depend not only on the excitation energy of the resonances but also and the relative probability to emit one or two neutrons from the two-neutron unbound state. Interestingly, it is possible that the $g_{7/2} \rightarrow g_{9/2}$ transition will directly feed a two-neutron unbound state, assuming the energy of the populated state follows the observed energy in ^{132}Sn and shell model predictions of E^{*}~7 MeV. Using the emission model by Kawano et al. [Kaw08] we predict a ratio of 60/30 between 1n and 2n emission. The exact value should be soon provided by the BRIKEN experiment analysis [Est17], but only with spectroscopic analysis we can find the exact GT resonance in order to validate the model assumptions.

The GT resonance in ^{134}Sn populated in beta decay of ^{134}In should be a pure $g_{7/2}^{-1}$ particle-hole excitation within ^{132}Sn core. Naively, the other neutron states such as $p_{3/2}$, $h_{9/2}$, $p_{1/2}$ and $f_{7/2}$ outside ^{132}Sn core should only contribute to the ^{134}Sn* wave function only as much as they contribute to the ^{134}In ground state. Here the GT transformation and beta delayed neutron emission to single particle states in ^{133}In will provide us with a spectroscopic probe of the degree of this configuration mixing in ^{134}In.

As mentioned earlier, other neutron single-particle states in ^{133}Sn will be populated in neutron emission from ^{134}In states fed via the first-forbidden decay mode. This second order process, with a more complex operator involves parity changing transition. The simple argument, points to the population of proton single particle states above Z=50, generating a proton particle-hole states, see Figure 4, but the configuration mixing effects, may also lead to population of neutron single particle states. Because of the phase space factor, the transitions to low lying states in the daughter nucleus can be very enhanced in a similar manner as GT decays. Hints of the population of neutron unbound states via forbidden transitions are seen in the decays of ^{132}Cd and ^{133}In.

The pair of ^{133}In and ^{134}In provides a rare case in the whole nuclear chart, where the impact of forbidden and GT decays on beta delayed neutron emission can be cleanly discerned due to the strong magicity of the ^{132}Sn core. The simple configurations expected for excited states makes them perfect test cases to test the validity of models describing neutron emission. The study of ^{134}In decay together with ^{133}In decay provides a strong foundational picture to understand of beta-delayed neutron emission process.

Technical Aspects

The experiment will be instrumented at the ISOLDE Decay Station using its standard set of 4 clover detectors, ~4% efficiency at 1 MeV, the IDS in-vacuum beta detector, 90% electron detection efficiency, and the newly commissioned IDS Neutron Detector . The angular acceptance for 26 bars at 100 cm is Ω=14.9% of 4π, and using 90% beta efficiency the total efficiency of the array is between 3 - 7%.The performance of this system was demonstrated during the ^{133}In decay experiment.

Beam Request

Table 1 summarizes the requested beam time. Due to the lack of beta-decaying isomers in even In isotopes, we request the hot Ta ion source along with the RILIS ion source in broadband mode. Enhancement of In release using RILIS has been observed in several experiments at ISOLDE [Dil02,Fra16], with yields of 8000 and 95 ions/uC for ^{132}In and ^{134}In respectively. The main isobaric components, and therefore contamination, in masses 132 and 134 are the relatively long lived isotopes of iodine and cesium. However, these are not neutron emitters, therefore they will not contribute to the background in IDSND. In the case of the A=^{134} isobar, ^{134}Sn has a neutron branching ratio of 17%. Recent experiments at IDS [Fra16,Mad17] showed an effectively complete suppression of Sn components using a combination of electromagnetic separation and RILIS.

In order to calibrate the detector response, we request 1 shift of ^{17}N beam. Molecular extraction of ^{17}N using a CaO target was recently demonstrated at ISOLDE, with yields of 100 ions/μC (IS605).

Table 1: Expected neutron rates. These calculations are done for 2 uC PS Booster beam and 50% transmission efficiency to IDS (n.c. = neutron converter)

	P_n(%)	**Yield (ion/μC)**	**IDSND Eff**	**Neutrons (1/h)**	**Shifts**	**Target**	**Source**
^{132}In	6.3%	8000	0.04	7.3 10^4	1	UC_X+n.c.	Hot Ta line and cavity + RILIS
^{134}In	65%	100	0.04	8.9$10^3$	9	UC_X+n.c.	Hot Ta line and cavity + RILIS
^{17}N	95.1%	100	0.04	1.8 10^4	1	CaO	Hot Ta line and cavity

Summary of requested shifts:

We request 11 shifts to collect at least 5 10^5 neutrons from the decay of both ^{132}In and ^{134}In. Assuming that forbidden transition are 2 orders of magnitude less likely to be populated than Gamow-Teller transitions, the collection time requested will ensure that about 10^3 neutrons are detected from states populated in forbidden decay. Beam time breaks down in 1 shift for ^{132}In, 9 shifts for ^{134}In and 1 shift for ^{17}N calibration.

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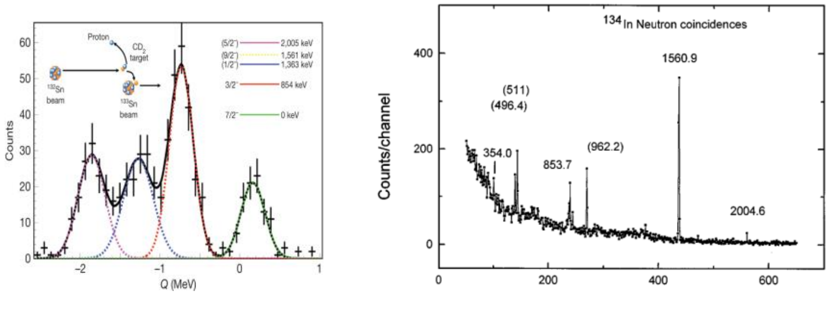

Figure 1. Experimental observation of single particle states in ^{133}Sn after the decay of ^{134}In by Hoff et al and by Jones et al. in the (d,p) reaction.

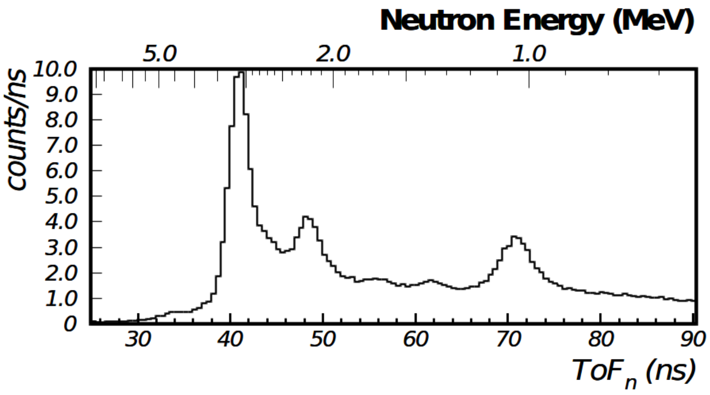

Figure 2. Preliminary neutron energy spectrum observed in the decay of ^{133}In by Madurga et al. The strongest neutron line at 3 MeV will most likely belong to GT transformation.

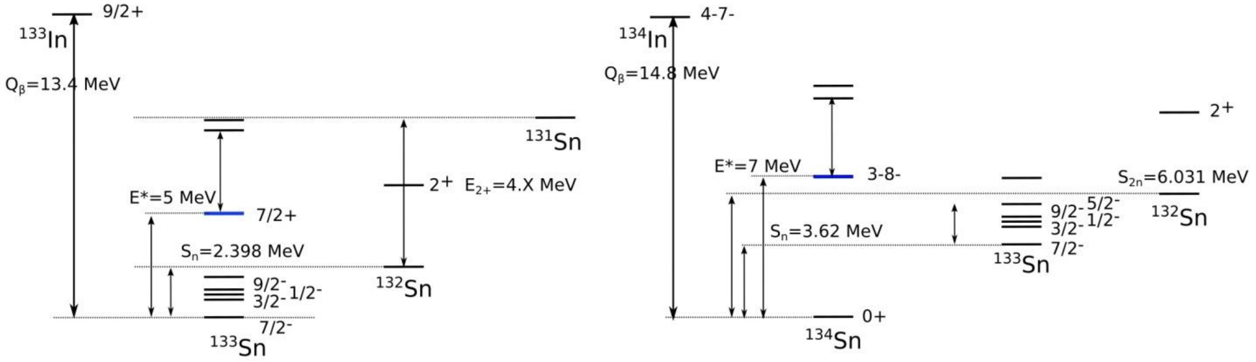

Figure 3. Decays of ^{133}In and ^{134}In. The key difference between ^{133}In and ^{134}In decays is the spin and parity of states populated states and the nature of states populated in the decay daughter, see In the case of ^{133}In, the final nucleus is the doubly magic ^{132}Sn, and very high excitation energy of the 2^+ state at 4041 keV makes it energetically unavailable to be populated in the decay of the main GT resonance. In the ^{134}In case, the neutron emission will end in ^{133}Sn [Hof96], which has several low-lying states identified as single particle neutron excitations [Jon10].

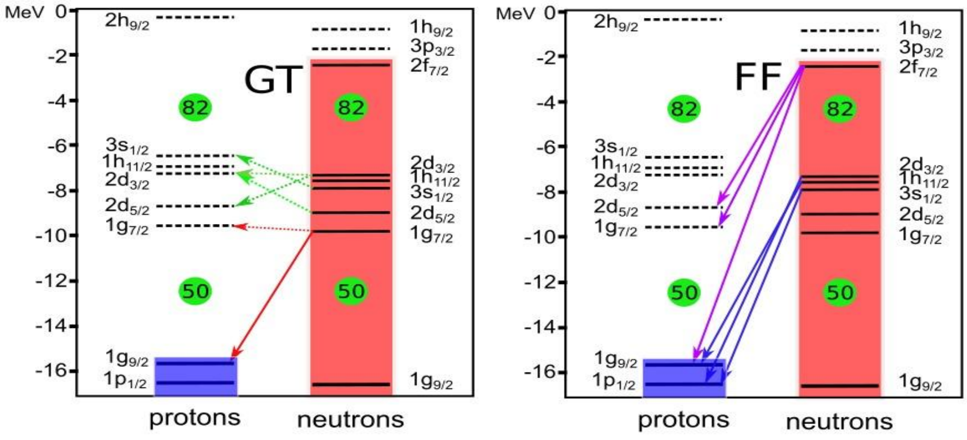

Figure 4. Single particle structure near ^{132}Sn and states populated in allowed (GT) and forbidden (FF) decays in the region. Single-particle states in ^{133}Sn will be populated in neutron emission from ^{134}In states fed via GT and the first-forbidden decay modes. Both GT and FF modes will populate the main $\nu g_{7/2}^{-1} f_{7/2}^{+1,3}$ configuration but also proton single particle states above Z=50.

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 Choose an item.	**Availability**	**Design and manufacturing**
[if relevant, name fixed ISOLDE installation: COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH]	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☒ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

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 the experiment/equipment]	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		

Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
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 (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
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]		

0.1 Hazard identification

3.2 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)