EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

**Clarification letter to the ISOLDE and Neutron Time-of-Flight Committee**

# Proposal INTC-P-559 - Total absorption spectroscopy of neutron-rich indium isotopes beyond N=82

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This clarification letter addresses the concerns of the INTC with respect to our INTC-P-559 proposal to investigate $\beta$ decay of $^{132-134}$In with the LUCRECIA total absorption spectrometer (TAS) [1].

The letter contains specific description of three goals we would like to achieve in the proposed experiment: obtain the Gamow-Teller (GT) strength distribution in the decay of $^{132-134}$In, understand the strong neutron vs. $\gamma$-ray competition in $^{132}$Sn region and find the last missing single-particle state in the region, the $i13/2$ neutron state. The last part of the letter addresses the issues of the analysis and de-convolution of TAS spectra in the context of availability of high-resolution data.

## Gamow-Teller strength distribution

The goal of these studies is to obtain the Gamow-Teller (GT) strength distribution ($B_{GT}$) in the decay of these exotic isotopes. The $B_{GT}$ deduced from the measured $\beta$ intensity can be compared to the calculated square of the GT transition matrix element, which allows to probe the predicting capabilities of nuclear models for $\beta$-decay properties far from stability. In the case of $^{132-134}$In, as well as for more exotic indium isotopes, the $\beta$-decay transition is dominated by the GT $\nu g_{7/2} \rightarrow \pi g_{9/2}$ transformation. The precise description of this transition will define the rate of $\beta$ decay in the whole southeast $^{132}$Sn region, which is important to provide reliable input for shell-model and r-process network calculations.
Due to the high efficiency of the LUCRECIA crystal and its geometry, covering a solid angle around the radioactive samples of nearly $4\pi$, the spectrometer has 90% total efficiency and over 60% peak efficency for the detection of 1 MeV $\gamma$-ray . Rather than detecting the individual $\gamma$ rays, a TAS detects the $\gamma$-ray cascades. Hence, the counts in the energy spectrum relates to the energy of the excited levels in the daughter nuclei and are given by the detector response-function to a given $\gamma$-ray cascade and to the $\beta$-feeding intensity ($I_\beta$). As it has already been demonstrated in a number of cases [2, 3, 4], this is the best method to obtain the 'real' $\beta$-feeding and avoid the so-called Pandemonium effect [5]. The real $\beta$-feeding patterns, which are needed to calculate the true GT strength distribution, are the main outcome of TAS measurements. There is no better-suited experimental approach to measure $B_{GT}$ than total absorption spectroscopy.
When GT transitions feed states above the neutron separation energy ($S_n$), as it happens in the decay of $^{133}$In, the energies and intensities of $\beta$-delayed neutrons must be measured

to obtain the intensities of the $\beta$ transitions and, consequently, the $B_{GT}$. However, strong neutron vs. $\gamma$-ray competition was observed also from levels fed by GT transitions in the $^{132}$Sn region [6, 7, 8] and needs to be better understood. This is only possible if the $\beta$-feeding followed by $\gamma$-ray decay is measured in a reliable way, as it is the case in the proposed experiment. The measurement of the neutron component alone is therefore insufficient to obtain the correct values of $\beta$-transition intensities.
In addition, due to the phase-space factor, even a small change in percentage for the $\beta$ feeding to highly excited states translates into a large change in the corresponding $B_{GT}$ value, leading to a systematic error in its determination. A TAS measurement of such decays is then essential for the precise evaluation of $B_{GT}$ function.

## Neutron vs. $\gamma$-ray competition

The existence of strong neutron-$\gamma$-ray competition is a topic that has attracted considerable interest over the past few years [11, 4], including, in particular, the $^{132}$Sn region [12, 6, 7], where electromagnetic transitions de-exciting a state over 3.5 MeV above $S_n$ were observed [7]. The mechanism of this phenomenon remains unclear. In some of these works nuclear structure arguments were used to explain the experimental results, e.g. in the work by Vaquero *et al.* [6] the observation of strong $\gamma$-ray emission from a neutron-unbound state, identified as the $h_{11/2}$ neutron-hole state in $^{133}$Sn, was explained as due to the small overlap of the wave functions of the initial and final states, with the expectation of the same effect for all hole states in the N=50-82 shell, in particular in $^{134}$Sn.
A different suggestion with respect to the mechanism of delayed neutron and $\gamma$-ray emission from neutron-unbound states was made in the work of Ref. [13], in which one- and two-neutrons emission probability ($P_{1n}$ and $P_{2n}$) in $\beta$ decay of $^{86,87}$Ga were measured. The observed $P_{1n} > P_{2n}$ for both isotopes was interpreted as a signature of dominating one-neutron emission from the two-neutron unbound excited states. The experimental results could not be described by the shell model alone, and the Hauser-Feshbach statistical model of particle and $\gamma$-ray emission from a compound nucleus had to be invoked. The work concluded that the use of a statistical description of neutron emission is relevant for the prediction of the decay properties of multi-neutron emitters with the consequence that it must be included in the r-process modeling [13]. As was shown in Ref. [13] such statistical description also applies to describe neutron vs. $\gamma$-ray competition. The systematic study of neutron-$\gamma$-ray competition from the neutron unbound states in the region southeast of $^{132}$Sn with efficient detection system will allow to gain a deeper insight into this phenomenon as well as to obtain quantitative information for $\gamma$ rays emitted from unbound states.
Another possible explanation of the existence of strong neutron-$\gamma$-ray competition in $^{132}$Sn region could be the presence of low-lying collective modes, which would decay directly by one or two very energetic $\gamma$-ray transitions. The existence of low-lying collective modes in the neutron rich tin isotopes has been shown through nuclear reactions [14, 15]. The proposed experiment is an opportunity to study the excitation of dipole strength through $\beta$-decay whenever the required spin and parity conditions are fulfilled.

The $\beta$-decay study of nuclei in the region of $^{132}$Sn using TAS techniques is the ideal strategy to examine the neutron vs. $\gamma$-ray competition for several of reasons:

- Large energy window for the neutron and $\gamma$-ray emission due to the large $Q_\beta$ and low $S_n$.
- Unique possibility to investigate the competition between neutron vs. $\gamma$-ray de-excitation in a simple system, which can be interpreted within single-particle picture.
- It has been demonstrated that the use of high-resolution and low-efficiency detectors underestimates the electromagnetic component for the decay of unbound neutron transitions [11, 4], proving the effectiveness of using TAS, which has a large sensitivity to small branches, to study the neutron vs. $\gamma$-ray competition phenomenon.

In addition to the above mentioned motivations, the study of neutron vs. $\gamma$-ray competition in several works was highlighted as having a great importance for r-process nucleosynthesis calculations [6, 11, 13].
In this context, in this proposal we want to address the systematic study of neutron vs. $\gamma$-ray competition from neutron-unbound states in the region southeast of $^{132}$Sn.

## 13/2$^+$ single-particle level

This proposal aims also at investigating the 13/2$^+$ single-particle (s.p.) level in $^{133}$Sn by looking at the delayed-neutron decay-branch of $^{134}$In $\beta$ decay. Due to the difference between the spin of the $^{133}$In ground state ($J^\pi$=9/2$^+$) and the 13/2$^+$ level, the latter is not populated directly in $\beta$ decay of $^{133}$In [7]. Nevertheless, it can be populated in the $\beta$-delayed neutron decay-branch of $^{134}$In. Given that $^{134}$In ground state has $J^\pi$ =(4$^-$–7$^-$), most likely $J^\pi$ = 7$^-$ [9], the main GT transitions will populate high-spin states above the neutron separation energy, as was observed for $^{133}$In decay. Neutrons emitted from these levels can feed high-spin excited states in $^{133}$Sn, including 13/2$^+$, because of the lower centrifugal barrier they face. The 13/2$^+$ s.p. level is expected to have an excitation energy of about 2.5 MeV [10], which is only around 100 keV above $S_n$. Its de-excitation can proceed by neutron emission only to the $^{132}$Sn $J^\pi$ =0$^+$ ground state, or by $\gamma$-ray emission to the $^{133}$Sn $J^\pi$ =7/2$^-$ ground state (E3 transition) or as a $\gamma$-ray cascade through the 9/2$^-$ state (M2 and M1 transitions). However, because of the large centrifugal barrier (l=6) the intensity of the neutron channel will be strongly suppressed. In addition, previous measurements indicate that in the $^{132}$Sn region the $\gamma$-ray intensities from unbound neutron levels are higher than it would result from neutron attenuation by the centrifugal barrier [6]. Given that the typical efficiency of neutron detectors is more than an order of magnitude lower than that of LUCRECIA, the measurement with a highly-efficient $\gamma$-ray detector is a key method to identify the last missing s.p. state in $^{133}$Sn.

## Data needed for TAS-spectra de-convolution

Knowledge of the de-excitation pattern of excited states populated in $\beta$ decay is an important aspect of the analysis of TAS spectra and quantifying the uncertainty stemming from incomplete information on the level schemes and decay patterns is important. Such study, in which the influence of an unknown de-excitation pattern in the analysis of TAS spectra, was investigated and reported by Tain and Cano-Ott [16]. The goal of the work was to quantify the systematic deviations that different assumptions on the $\gamma$-ray de-excitation paths might introduce in the extracted $\beta$-intensity distributions. In order to do this, the energy spectrum of a fictional nucleus was first simulated and then analyzed using both realistic and unrealistic $\gamma$-ray de-excitition paths. The deviations between the referenced $\beta$-intensity distribution and that obtained by applying unrealistic assumptions were only sightly larger than those obtained using realistic assumptions. The conclusion of the paper was that the $\beta$-strength distribution to high-energy levels can be determined within a few percent, independently on the assumption used for the $\gamma$-ray de-excitation paths. In the low-energy part of the spectrum, where the level density is smaller, the $\beta$-strength distribution obtained is more sensitive to the assumptions made, but, if these are reasonable, the differences are not larger than 10%–20% [16].

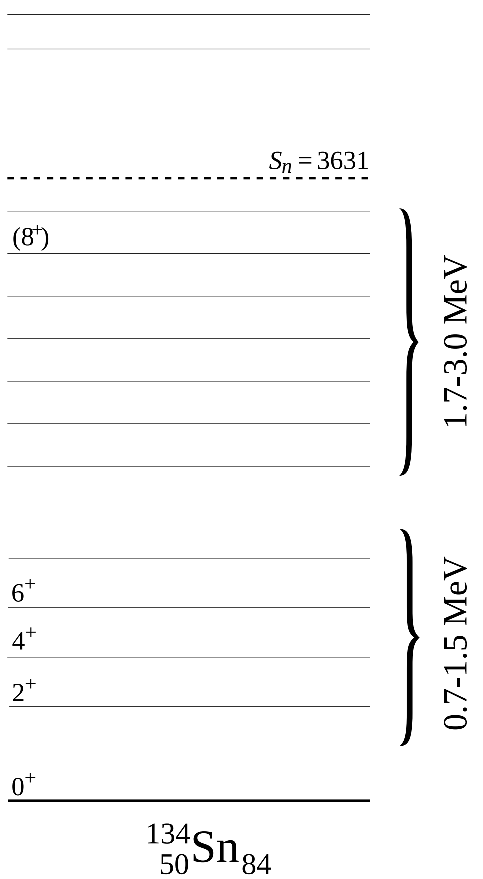


Figure 1: Schematic representation of the $^{134}$Sn level scheme obtained from experiments [17, 18]. Drawing not to scale.

High-resolution data for the $^{132,133}$In decay was collected at IDS recently. For both nuclei, rich decay schemes, sufficient to perform a precise deconvolution of the TAS spectra, were obtained. Their analysis is completed and recently published [7, 12].

As far as decay data of $^{134}$In is concerned, four excited states in the $\beta$ daughter $^{134}$Sn are known from $\gamma$ rays observed in the spontaneous fission of $^{248}$Cm [17].

A more complete level scheme of $^{134}$Sn was obtained recently from the study of $\beta$-decay of $^{134}$In and $\beta$-n-decay of $^{135}$In at IDS ISOLDE [8, 18]. The analysis of the two data sets is completed and a manuscript on the results obtained is going to be submitted for publication [18]. In brief, 11 new excited states including lying well above the neutron-separation energy were identified, see Figure 1. Such information on the decay scheme of $^{134}$Sn is sufficient for a precise de-convolution of the TAS spectrum.

In addition to the experimental data, theoretical predictions of large-scale shell-model calculations with and without core excitation [19, 20] can be also used to make reasonable assumptions about the $\gamma$-ray deexcitation pattern in $^{134}$Sn.

In conclusion, total absorption spectroscopy of neutron-rich indium isotopes beyond N=82 at ISOLDE is the best method to do a proper measurement of the $\beta$ feeding and to extract the $B_{GT}$ for the $^{132,133,134}$In decays.
The information will be key to understand the $\gamma$-ray emission from neutron-unbound states in the region, and it is a necessary complement to a direct neutron emission measurements. TAS measurements will also provide the best method to look for the last missing single-particle state in the region, the elusive $i13/2$ neutron state.
The existing high-resolution $\gamma$-ray spectroscopy data, mainly from the IS610 experiment at ISOLDE, is largely sufficient as input for the TAS analysis.

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