# ISOMER SPECTROSCOPY OF IN-FLIGHT FISSION FRAGMENTS NEAR $^{132}$SN AT THE GSI FRAGMENT SEPARATOR

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At GSI-Darmstadt, a variety of neutron-rich isotopes in the vicinity of $^{132}$Sn have been produced in relativistic projectile fission of $^{238}$U. The fragments of interest were mass separated and identified using the fragment separator FRS before being implanted inside a high-resolution Ge-detector array. Delayed heavy-ion tagged γ-ray spectroscopy was applied to study the decay of relatively long-lived ($T_{1/2}$ in the 100ns - 100 μs range) isomeric states in the implanted fission fragments, including new isomers in $^{126-128}$In and $^{125}$Cd.

## 1. Introduction

The doubly magic nucleus $^{132}$Sn (Z=50, N=82) marks one of only two double shell closures now accessible in the very neutron rich (N/Z>1.6) region of the nuclear chart. The shell structure and residual interaction at these fix-points are intima-tely related to many important issues, such as the proposed quenching of shell-closure strength for extremely neutron rich nuclei, the development of low-lying deformed intruder configurations, and the astrophysical r-process. That the detailed understanding of neutron rich systems far from stability is far from complete is illustrated by the different predictions of e.g. shell evolution obtained by various theoretical approaches. More experimental data on both global nuclear properties as well as spin-dependent ones are thus urgently needed for neutron rich systems.

Recently, ion-tagged delayed γ-coincidence spectroscopy of isomeric states produced directly in nuclear reactions [1] has emerged as a successful alternative to β-decay studies for studying excited states in very neutron rich nuclei far from stability. We have applied this method to produce and investigate μs-range isomers in the region around $^{132}$Sn using projectile fission

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induced by a Pb target. In this reaction, the projectile is electromagnetically excited and then fissions. The resultant relatively cold fission products subsequently deexcite, mainly via γ-ray emission. In this latter process, isomeric states, if present in the final nucleus, may be populated directly or "from above" by acting as a trap for γ-ray cascades from states of higher spin.

The spectroscopy of isomeric decays provide a unique and quite selective method to probe not only transition rates but also level energies in the nuclei in which they occur. The method is an ideal complement to β-decay and in-beam experiments, which often require higher count rates. From the isomer decay pattern as well as the properties of intermediate states populated in the decay, entities such as single-particle energies, residual interaction strength, shell occupation and development of collectivity can be extracted.

Previous investigations of the tin region isomers include studies of fission product ß-decay after ISOL mass separation (limited by the availability of high-spin ß-decay parents), measurements of prompt γ-decay of fission products with large Ge-detector arrays (limited by low production yields to the Z>50, N>82 region), and experiments at the GSI fragment separator [2].

This paper reports on the results of a recent experiment performed at GSI-Darmstadt, where we searched for and studied relatively long-lived (100ns - 1ms) isomeric states in neutron rich isotopes in the region of $^{132}$Sn. The study hopes to provide deeper insight into nuclear structure far from stability as well as the role of angular momentum in the production reaction.

## 2. Experiment

The present experiment was performed in July-August 2002 at the FRagment Separator [3] (FRS) at GSI, Darmstadt. Neutron-rich nuclei in the vicinity of $^{132}$Sn were produced by projectile fission of $^{238}$U at the relativistic energy of 732 MeV/nucleon impinging on a 1 g/cm$^2$ Pb target. The average beam intensity from the SIS heavy ion synchrotron was $4{\cdot}10^8$ ions per cycle, with each cycle consisting of 5 s acceleration and 5 seconds extraction. The data presented here were obtained during an effective measurement time of 8 hours with the FRS optimized for the transmission of $^{130}$Sn.

The ions of interest were separated by combining magnetic analysis with energy loss in matter [3]. The FRS was operated in a standard achromatic mode, with a wedge-shaped aluminium degrader with thickness selected to 50% of the range of the fragments of interest placed at the intermediate dispersive focal plane of the spectrometer. Figure 1 shows a schematic view of the FRS and the associated detectors setup.

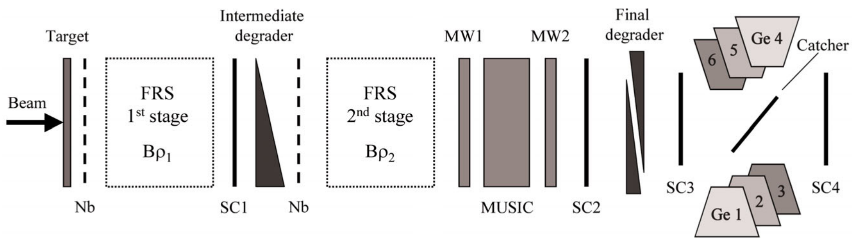


Figure 1. Schematic view of the FRS and the experimental setup.

Under the present conditions, typically about 20 different fragment species distributed over 3-4 elements were transmitted at each setting of the separator. The fragment identification was performed according to the so-called Bρ-ΔE-TOF method, which combines information on the particle trajectories (from the magnetic rigidity Bρ and position information) with measurements of velocity (through time-of-flight (TOF)) in the second half of the FRS and energy loss (ΔE) at the final focus to obtain the proton number Z and mass-to-charge ratio A/q for all transmitted fragments. At the relativistic energies used, the percentage of non-fully stripped ions in the tin region is small, leading to q=Z. Figure 2 illustrates the good resolution that was obtained, resulting in unambiguous particle identification.

At the focal plane of the FRS, the transmitted fragments were slowed down in a variable-thickness aluminium degrader before being implanted in a plastic catcher foil. The implantation process was controlled by means of scintillator detectors. The catcher was surrounded by six segmented Clover-type detectors in which delayed γ-rays emitted by the implanted ions were detected.

The energy and time of all "first hits" in the Ge detectors within a 80 μs interval following the implantation of an ion were recorded together with the particle identification information for the respective ion. This allowed the construction of heavy ion-gated γ-ray energy versus time matrices for both prompt and delayed ion-gamma coincidences.

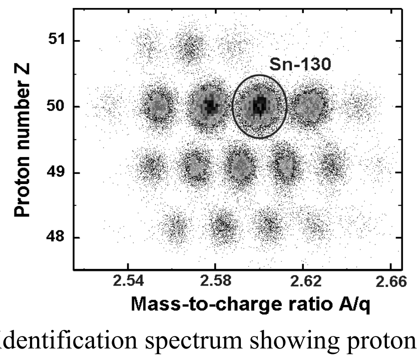


Figure 2. Particle identification spectrum showing proton number Z versus the mass-to-charge ratio A/q for fragments reaching the implantation setup with the FRS optimized for $^{130}$Sn

## 3. Analysis and preliminary results

As the analysis is still in progress, the results presented here should be considered *preliminary*. Nevertheless, it seems clear that the present study may add considerably to the experimental data for selected ions "southwest" of $^{132}$Sn.

Figures 3 and 4 show delayed γ-ray energy spectra of selected tin, cadmium and indium fragments exhibiting isomeric decays. The spectra were obtained by projecting the above mentioned γ-ray energy versus time matrices for the time interval 1-35 μs after implantation. This suppresses most of the "prompt" events which mainly result from radiation produced during the slowing-down process and/or fragments breaking up in the degrader or catcher, but especially at lower energies the background remains high, as illustrated e.g. by the $^{130}$Sn spectrum.

By conversely defining gates on γ-ray energies, the decay time information of the transitions of interest could be obtained by matrix projection. To reduce the influence of prompt radiation, time spectra from background gates were subtracted before fitting the resultant distributions with a single exponential decay on top of a flat background. Table 1 summarizes the properties of the isomers observed in the present study, while Figure 5 illustrates such time spectra with fits for the isomers observed in the present experiment.

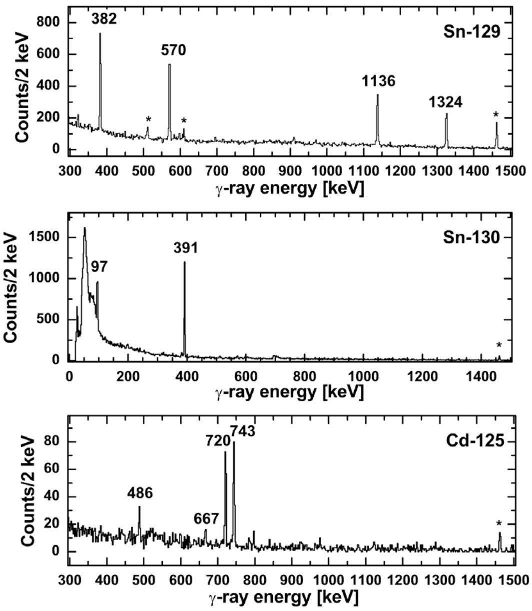


Figure 3. Gamma-ray spectra recorded in delayed coincidence (1.0-35.0 μs) with Sn and Cd fission fragments. Background activity is labeled by asterisks.

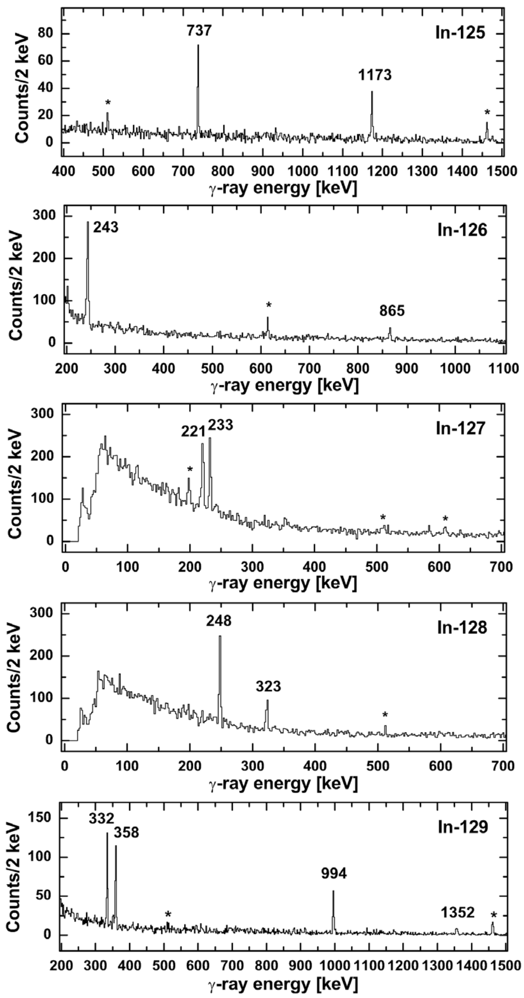


Figure 4. Gamma-ray spectra recorded in delayed coincidence (Δt=1.0-35.0 μs) with In fission fragments. Background activity is labeled by asterisks.

## 4. Discussion

In the following, we briefly discuss the *preliminary* results obtained so far for some of the individual isomers observed in the present study:

*$^{129}$Sn:* The half-life we obtain, 3.9(4) μs, is in good agreement with Genevey *et al.*'s value of 3.6(2) μs [4] for a proposed $19/2^+$ isomer. This could

indicate that in-flight Pb-target induced fission does not strongly populate the higher-lying 2.4(2) μs $23/2^+$ isomer [4].

*$^{130}$Sn*: The good agreement between our half-life value of 1.5(2) μs with the 1.61(15) μs measured by Fogelberg *et al.* for the $10^+$ isomeric state [5] gives us confidence in the experimental technique and the evaluation procedure.

*$^{125}$Cd:* This previously unknown isomer shows two strong γ-transitions with similar energy, intensity and decay behavior. Comparing with the A=120-130 tin isotopes, where the lowest lying state is alternately $2^+$ or $15/2^-$, a possible interpretation of this decay would be a cascade starting with a hindered M2 transition deexciting a $19/2^+$ isomer via an $15/2^-$ level down to a known $(11/2^-)$ state, which could be the ground state (Ref. [8] quotes its energy as 50(70) keV.) Two much weaker delayed γ-transitions at 486 and 667 keV are also observed.

*$^{125}$In:* We observe an isomer as first observed by Fogelberg *et al.* [6], decaying by a strong cascade of 737 and 1173 keV transitions.

*$^{126}$In:* This previously unreported isomer exhibits a strong γ-ray at 244 keV. In analogy with $^{128}$In (see below), we tentatively interpret this as the primary isomeric transition connecting the $1^-$ member of the $\pi g_{9/2}^{-1} \nu h11_{/2}^{-1}$ multiplet with the $3^+$ ground state. The origin of the much weaker 614 and 865 keV transitions also present in the delayed γ-ray spectrum is presently not understood.

*$^{127}$In:* We observe an isomer decaying with only two γ-rays of similar intensity, energy and half-life. The decay pattern and half-life, which show very little resemblance to the neighbors $^{125,129}$In (see Fig. 4 and Table 1), could belong to an isomer on top of the presumably long-lived $23/2^-$ state [6], the decay of which escapes the observation time window of our experiment. We

Table 1. Some properties of isomers observed in the present study.

| *Nucleus* | *Spin* | *Observed delayed γ-rays* [keV]* | *Half-life* [μs]* This work | *Previous* |
|---|---|---|---|---|
| $^{129}$Sn | $19/2^+$ | 382, 570, 1136, 1324 | 3.9(4) | 3.6(2) [4] |
| $^{130}$Sn | $10^+$ | 97, 391 | 1.5(2) | 1.61(15) [5] |
| $^{125}$Cd | $(19/2^+)$ | 720, 743 | 14(2) | |
| $^{125}$Cd | | 486, 667 | | |
| $^{125}$In | $19/2^+$ | 737, 1173 | 13(2) | 9.4(6) [6] |
| $^{126}$In | $(1^-)$ | 244 | 30(3) | |
| $^{126}$In | | 614, 865 | | |
| $^{127}$In | $(29/2^+)$ | 221, 233 | 13(2) | |
| $^{128}$In | $(1^-)$ | 248 | 170(80) | >10μs [7] |
| $^{128}$In | | 323 | | |
| $^{129}$In | $(17/2^-)$ | 332, 358, 994, 1352 | 11(2) | 2.0(5) [4] |

* Values are preliminary and may change as the analysis progresses.

tentatively assign a spin of $(29/2^{+})$ from the $\pi g_{9/2}^{-1}\nu h_{11/2}^{-2}$ configuration to this proposed high-lying state, which is likely present also in the neighbors but may have escaped detection up to now due to its half-life being too short or long [6].

*$^{128}$In:* Our measurement confirms the isomeric $(1^{-})$ state observed by Fogelberg [7] to deexcite to the $(3)^{+}$ ground state by a 248 keV $\gamma$-ray with a quite long half-life. The weaker transition at 323 keV present in our spectrum could connect a second, higher-lying $(1^{-})$ or $(5^{+})$ isomeric level to the $(3)^{+}$ ground state. Such states are expected from the $\pi p_{1/2}\nu d_{3/2}$ and $\pi p_{1/2}\nu h_{11/2}$ configurations.

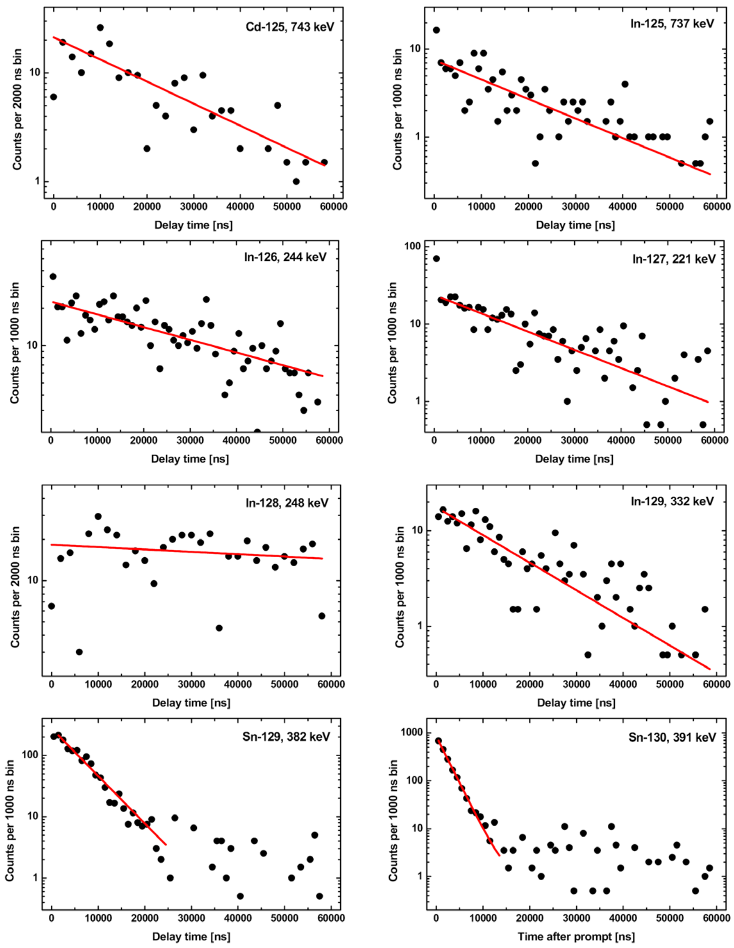


Figure 5. Background-subtracted decay time distributions with one-exponential fits for selected $\gamma$-transitions. See Table 1 for deduced half-lives.

$^{129}$*In:* We observe an isomeric decay with the same γ-transitions as reported by Genevey *et al.* [4] but exhibiting a much longer half-life of 11(2) μs. This decay can probably be interpreted as that of a ($17/2^-$) state, as any higher spin would not allow for the know 700 ms ($23/2^-$) isomer at ~1900 keV observed by Fogelberg *et al.* [6], and positive parity would enable a fast E2 transition to the ($13/2^+$) state at 1352 keV. The existence of an undedected low-energy E1 primary isomeric transition cannot, however, be excluded from our data.

## 5. Outlook

Although this and other recent studies directed at nuclei close to doubly magic $^{132}$Sn have provided a wealth of new data, their interpretation and the details of nuclear structure in this region is not yet clear. A number of outstanding issues remain, including the possibility of shell quenching. At GSI, the program of isomer spectroscopy of neutron rich exotic nuclei is planned to be continued as part of the stopped-beam phase of the RISING project [9].

In addition to this and further experimental efforts elsewhere, we would like to encourage an active and continuous involvement of the nuclear structure shell model theory community, whose help to develop and perform calculations using realistic interactions, especially for nuclei requiring large model spaces is much appreciated.

## References

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