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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

**Addendum to the ISOLDE and Neutron Time-of-Flight Committee**

# Probing the magicity and shell evolution in the vicinity of $N = 50$ with high-resolution laser spectroscopy of $^{81,82}$Zn isotopes Addendum: Laser-assisted decay spectroscopy of $^{75m,79m}$Zn

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**Abstract:** Following the successful IS682 campaign on the laser spectroscopy of neutron-rich zinc isotopes in the vicinity of $N = 50$ and the recent development of a tape station for the CRIS Decay Spectroscopy Station, we present here an addendum to study the decay spectroscopy of nuclear-state purified beams of ground state and isomer in $^{75,79}$Zn to investigate shape coexistence in the $N = 50$ region.

**Summary of requested shifts:** 17 shifts, (split into 1 run over 1 year)

# 1 Report on the first IS682 campaign

In the original proposal for IS682, we set out to answer the following 3 questions [1]:

1. What is the ground-state spin of $^{81}$Zn and how does the $1/2^+$ state evolve in $N = 51$ isotones?

2. Is the ground-state of $^{81}$Zn compatible with a single-particle description?

3. How does the mean-square charge radii trend and local odd-even staggering behave beyond $N = 50$?

We received 16 shifts to answer those questions on 23$^{\text{rd}}$-29$^{\text{th}}$ August 2023 with the Collinear Resonance Ionization Spectroscopy (CRIS) technique [2, 3], from a $UC_x$ target equipped with both a neutron converter and a quartz transfer line. The beam time was successful and the data acquired revealed the sought-after information, using the ionization scheme shown on Fig. 1. In particular, the nuclear spin and electromagnetic moments of $^{81}$Zn could be determined and compared to effective moments in the region. The changes in mean-square charge radii up to $^{82}$Zn could be determined, revealing the change of radius at the $N = 50$ shell closure. A sample of the collected spectra is presented in Fig. 1. The data are currently under analysis and will be the subject of several publications in the near future. Discussions are ongoing with several theory groups to support the interpretation of the findings [4, 5].

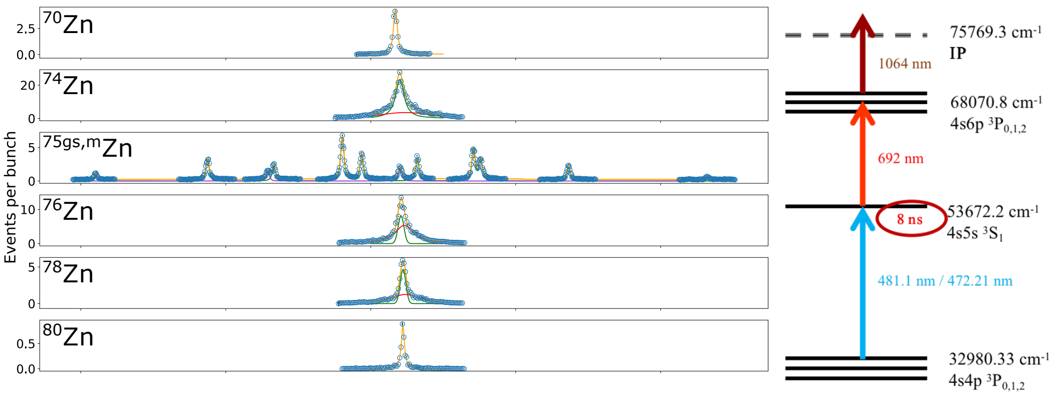


Figure 1: (left) Overview of the data collected on $^{70,74,75,76,78,80}$Zn during the 2023 campaign at the CRIS experiment at ISOLDE. The structure of $^{75m}$Zn spreads over but a few GHz and cannot be revealed or separated by in-source techniques. Additional data were collected on $^{81,82}$Zn. (Right) Ionization scheme used for Zn at CRIS; the first transition at 481 nm is the one used for the study of the laser spectroscopy.

# 2 Scientific context

Isomerism is often encountered in the odd-$A$ neutron-rich zinc isotopes. This effect arises mostly from the progressive filling of the neutron $g_{9/2}$ orbital between $N = 40$ and $N = 50$

Table 1: Overview of the spin and half-life of the neutron-rich zinc isotopes between $N = 40$ and $N = 50$.

| Isotope | $^{71}$Zn | $^{73}$Zn | $^{75}$Zn | $^{77}$Zn | $^{79}$Zn |
|---|---|---|---|---|---|
| g.s. spin | $1/2^-$ | $1/2^-$ | $7/2^+$ | $7/2^+$ | $9/2^+$ |
| g.s. half-life | 2.42 min | 24.5 s | 10.2 s | 2.08 s | 0.746 s |
| isomer spin | $9/2^+$ | $5/2^+$ | $1/2^-$ | $1/2^-$ | $1/2^+$ |
| isomer half-life | 4.14 h | 13 ms | - | 1.05 s | > 200 ms |

and the competition with particle-hole intruder states involving the $pf$ orbitals below $N = 40$, in particular the $p_{1/2}$ orbital that may give rise to a $1/2^-$ state. Meanwhile, excitation beyond the $N = 50$ shell may populate states within the $sd$ orbitals, in particular the $s_{1/2}$ orbital that may give rise to a $1/2^+$ state. This results in the distribution of ground and isomeric states in neutron-rich, odd-$A$ zinc isotopes presented in Table 1.
While most of these isomers have been investigated in detail, there remain questions for $^{75,79}$Zn concerning their half-lives and decay modes.

## 2.1 $^{75}$Zn

First proposed from the decay spectroscopy study of $^{75}$Cu at HRIBF in ORNL [6], the $1/2^-$ isomer in $^{75}$Zn was fully established upon the investigation of its hyperfine structure by COLLAPS at CERN [7]. The comparison between the experimental magnetic dipole moment and the nuclear shell model calculations concluded that the state was dominated by a single neutron in the $p_{1/2}$ orbital. However, no additional information is available on its half-life or decay mode. The NUBASE proposes a half-life of 5 s for $^{75m}$Zn, based on systematics in the region [8]. The observation of this isomer by the COLLAPS experiment suggests that the half-life is sufficient for release from an ISOLDE target and bunching in the ISCOOL radio-frequency quadrupole buncher, which is compatible with this prediction.

## 2.2 $^{79}$Zn

This isomer was first observed in a transfer reaction with the MiniBall spectrometer at REX-ISOLDE [9]. It was then investigated by COLLAPS, confirming its existence and studying its structure through its nuclear spin, magnetic dipole moment, and changes in mean-square charged radius [10]. From those combined experiments, it could be concluded that this state is very different from the other isomers across the neutron-rich isotopic chain. Instead of a single neutron hole in the $p_{1/2}$ orbital below $N = 40$, it appears to arise from a neutron excitation across the $N = 50$ shell closure to the neutron $s_{1/2}$ orbital. Moreover, from its large charge radius difference with the ground state, it can be inferred that this state posseses a large deformation, labeling this as a case of shape coexistence close to the $N = 50$ shell closure [11].
During the laser spectroscopy experiment at COLLAPS, various trapping times in ISCOOL were compared without showing any effect on the signal intensity [10]. From this, it could be concluded that the half-life of that isomer is at least 200 ms.

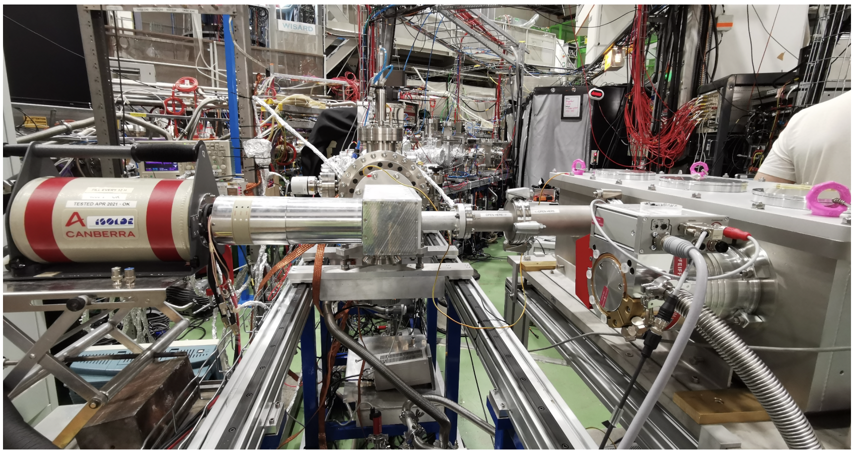


Figure 2: Experimental commissioning of the CRIS DSS tape station during the 2023 campaign of IS683.

The recent Coulomb excitation work performed witih MiniBall at HIE-ISOLDE has provided additional knowledge on this isomer in $^{79}$Zn. However, it did not provide any additional information on its decay to $^{79}$Ga [12].
Given the high difference in spin between the two long-lived states in $^{79}$Zn, they will populate states with very different spins in the daughter nucleus $^{79}$Ga, as already observed in $^{75}$Zn during out preliminary test. Moreover, the different shapes of those states might further skew which states are populated in the daughter nucleus, hereby giving access to new information to reveal shape coexistence in $^{79}$Ga.

# 3 CRIS-assisted decay spectroscopy

The CRIS experiment at ISOLDE is a well established setup to perform laser spectroscopy of exotic isotopes and radioactive molecules. It receives bunched beams from ISCOOL, which are then sent through an alkali vapor for neutralization and subsequently irradiated by a series of lasers in resonance with an ionization scheme specific to the element of interest. Based on this technique, high resolution laser spectroscopy can be performed by scanning either the laser frequency or the beam energy and monitoring the ion count rate as a function of the laser frequency in the frame of reference of the atom [3].
From its early years, the CRIS setup has featured a decay spectroscopy station [13, 14]. It assists the laser spectroscopy by monitoring the production of laser ions from decays rather than ion counting, which can be crucial when the yield of the isotope (or isomer) of interest is many orders of magnitude than contamination present in the beam [15]. It may also be used in separating the hyperfine structure of different isomers of the same isotope, especially when peaks are overlapping [16]. Finally, it may also be used to study the decay properties of a beam purified within the CRIS beam line, as demonstrated in the study of the decay chains of $^{204,206}$Fr [16, 17].
The original CRIS Decay Spectroscopy Station (DSS) was based on the use of a finite number of ultra thin carbon foils ($\sim 90\,$nm) to facilitate the study of $\alpha$-emitting nuclei like $^{204,206}$Fr [13, 14, 16, 17]. However, this approach was not adapted for $\beta$-emitting nuclei,

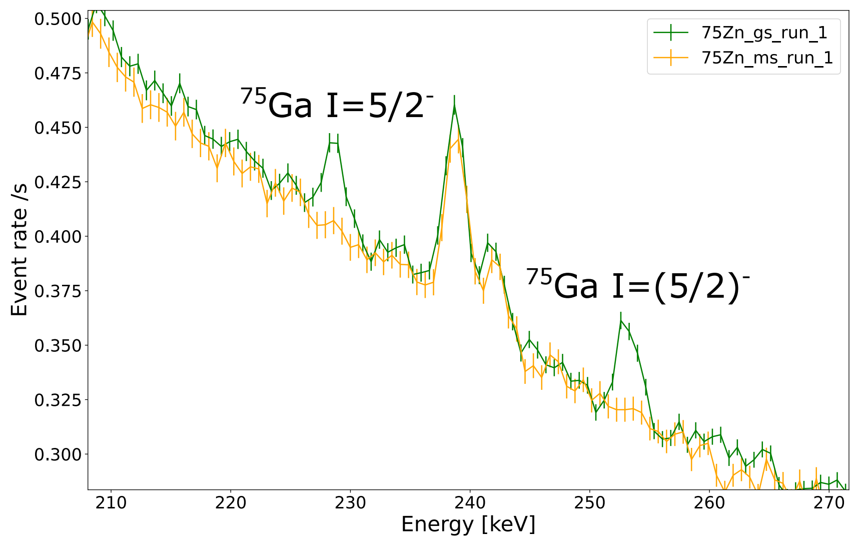


Figure 3: Single $\gamma$-ray spectra of $^{75}$Zn with the laser set on resonance for the ground state (green) or the isomer (orange). The two peaks at 229 keV and 254 keV populate high-spin levels in the daughter $^{75}$Ga (spin $5/2^-$), which are not populated in the decay of the low-spin isomer.

which long-lived progeny create substantial background. A traditional approach around this problem is the use of a long tape of, e.g., aluminized Mylar. Such a tape system has been developed for the CRIS DSS, based on the existing tape system of the ISOLDE Decay Station [18], and was commissioned during the 2023 campaign of IS682, as shown in Fig. 2. The CRIS DSS2 chamber used during that campaign consists in an aluminium chamber specifically designed for $\gamma$-ray spectroscopy. It was coupled to the tape and equipped with two silicon detectors, one of which had a hole to let the beam through, and a high-purity germanium detector was placed outside to record $\gamma$ rays following the $\beta$ decay.

During the 2023 campaign, the main aim was the study of $^{81,82}$Zn, which are high-energy $\beta$ emitters ($Q_{\beta^-} > 10$ MeV), while the possible contaminants were expected to be stable or have low-energy $\beta$ emissions. The detectors had thus been shielded with a layer of aluminium to differentiate between the different-energy $\beta$ particles. As a consequence, the particle detection was particularly inefficient when the system was commissioned with isomeric beams of $^{75g}$Zn and $^{75m}$Zn. Nonetheless, the activity removal with the tape could be demonstrated and single $\gamma$-ray spectra could be recorded. In Fig. 3, we present an overlay of the single $\gamma$-ray spectra collected for the ground-state (green) or the isomer (orange). This shows that the $\gamma$ rays at 229 keV and 254 keV are only present in the decay of the ground state, as they represent the decay of higher spin states in the daughter $^{75}$Ga nucleus (with spin $5/2^-$), which are not populated in the decay of the low-spin isomer.

Since then, a new plastic scintillator has been developed for the efficient detection of $\beta$ particles with the CRIS DSS. The design, shown in Fig. 4, has been completed and the setup is assembled. The new detector will be implemented during the year-end technical stop 2024-25 to be ready for the 2025 campaign. Moreover, we shall implement the

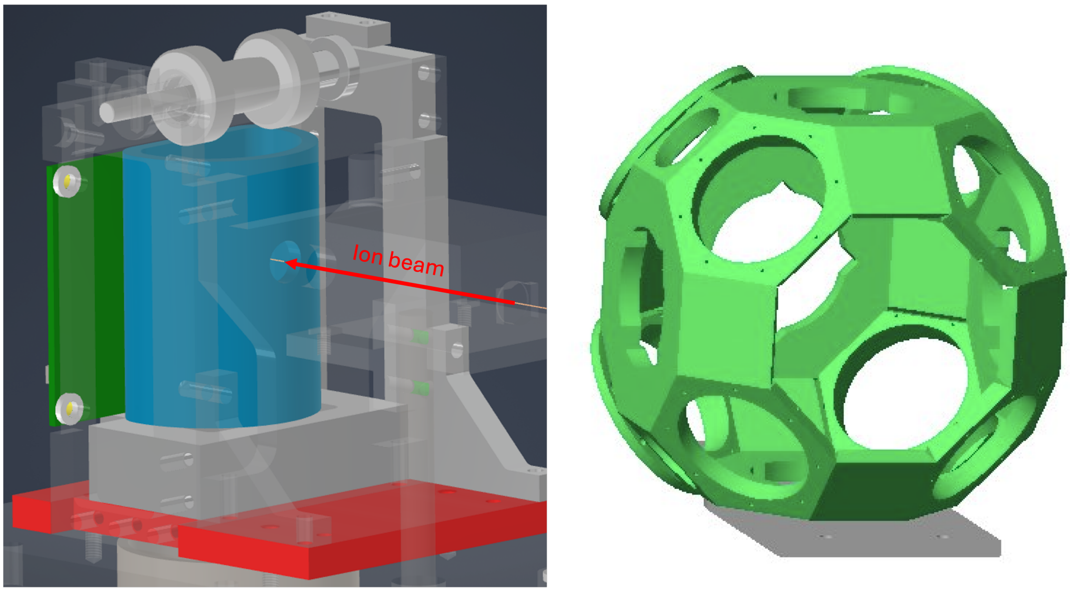


Figure 4: (Left) Design of the new CRIS DSS scintillator for the efficient detection of $\beta$ particles ($> 50\%$). (Right) The OSIRIS HPGe support frame previously used at the ISOLDE Decay Station.

OSIRIS support structure (see Fig. 4), previously used at IDS, to surround the CRIS DSS2 chamber with up to 4 high-purity germanium clover-type detectors from KU Leuven and IFIN-HH.

## 4 Request

We shall determine the ground-state properties (half-life, decay mode) of $^{75,79}$Zn and the $\gamma$-ray emissions in the daughter nuclei $^{75,79}$Ga using radioactive ion beams purified with the CRIS technique. We shall employ the new tape station in combination with the CRIS DSS2 chamber, surrounded by up to 4 HPGe clovers. This study cannot be performed by purification of the Zn isomers in the source, not even using the recently developed PI-LIST, due to the narrow and overlapping hyperfine structure of $^{75,79}$Zn, shown in Fig. 1. Based on the first campaign of IS682, we have determined the rates on resonance for the isotopes of interest, as shown in Table 2, from a UC$_x$ target equiped with a neutron converter and a quartz line, using RILIS to produce the Zn beams. We then evaluated how to reach 10 000 counts in representative $\gamma$-rays with medium intensities in the known decay schemes of $^{75,79}$Zn: in $^{75}$Zn, we considered 10 000 counts in the 178 keV $\gamma$ ray with 0.58% absolute intensity, while for $^{79}$Zn we considered 10 000 counts in the 802.5 keV $\gamma$ ray with 5.9% efficiency. We considered the $\gamma$-ray detection efficiency for the proposed geometry based on the extended simulation of a similar geometry in the early days of IDS, giving respectively 8% and 3% at the aforementioned energies. Finally, we request 3 shifts to set up the CRIS experiment to purify the zinc beams. Based on these, we present the shift request in Table 2, for a total of **17 shifts**.

Table 2: Measured rates and requested shifts for the study of the decay of $^{75,79}$Zn with the CRIS DSS.

| Isotope | Rate | Shifts ground-state | Shifts isomer | Total |
|---|---|---|---|---|
| $^{75}$Zn | 600 per s | 1 | 1 | 2 |
| $^{79}$Zn | 30 per s | 6 | 6 | 12 |
| | | | Setup | 3 |
| | | | **TOTAL** | **17** |

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# 5 Details for the Technical Advisory Committee

## 5.1 General information

Describe the setup which will be used for the measurement. If necessary, copy the list for each setup used.

- ☒ Permanent ISOLDE setup: *CRIS*
  - ☒ To be used without any modification
  - ☐ To be modified: *Short description of required modifications.*
- ☐ Travelling setup (*Contact the ISOLDE physics coordinator with details.*)
  - ☐ Existing setup, used previously at ISOLDE: *Specify name and IS-number(s)*
  - ☐ Existing setup, not yet used at ISOLDE: *Short description*
  - ☐ New setup: *Short description*

## 5.2 Beam production

For any inquiries related to this matter, reach out to the target team and/or RILIS (please do not wait until the last minute!). For Letters of Intent focusing on element (or isotope) specific beam development, this section can be filled in more loosely.

- Requested beams:

| Isotope | Production yield in focal point of the separator (/$\mu$C) | Minimum required rate at experiment (pps) | $t_{1/2}$ |
|---|---|---|---|
| $^{75}$Zn | $> 10^4$ | $> 10^4$ | 10.2 s |
| $^{79}$Zn | $> 10^4$ | $> 10^4$ | 0.746 s |

- Yields presented from the original proposal and confirmed during the 2023 campaign of IS682
- Target - ion source combination: $UC_x$
- RILIS for Zn
  - ☐ Special requirements: No
- Additional features?
  - ☒ Neutron converter against proton-rich Rb/Sr
  - ☐ Other: quartz against proton-rich Rb/Sr
- Expected contaminants: isobaric $^{75}$Ga ($5 \times 10^7/\mu$C) and $^{79}$Ga ($5 \times 10^6/\mu$C)
- Acceptable level of contaminants: limited by ISCOOL overfilling
- Can the experiment accept molecular beams? NO
- Are there any potential synergies (same element/isotope) with other proposals and LOIs that you are aware of? Not that we are aware of.

## 5.3 HIE-ISOLDE

## 5.4 Shift breakdown

The beam request only includes the shifts requiring radioactive beam, but, for practical purposes, an overview of all the shifts is requested here. Don't forget to include:

- Isotopes/isomers for which the yield need to be determined
- Shifts requiring stable beam (indicate which isotopes, if important) for setup, calibration, etc. Also include if stable beam from the REX-EBIS is required.

An example can be found below, please adapt to your needs. Copy the table if the beam time request is split over several runs.

**Summary of requested shifts:**

| **With protons** | Requested shifts |
|---|---|
| CRIS setup with radioactive $^{75}$Zn and $^{79}$Zn | 3 |
| Data taking, $^{75g}$Zn | 1 |
| Data taking, $^{75m}$Zn | 1 |
| Data taking, $^{79g}$Zn | 6 |
| Data taking, $^{79m}$Zn | 6 |
| **Without protons** | Requested shifts |
| CRIS setup with stable $^{70}$Zn | 3 |

## 5.5 Health, Safety and Environmental aspects

### 5.5.1 Radiation Protection

- If radioactive sources are required:
  - Purpose? Calibration
  - Isotopic composition? $^{60}$Co, $^{133}$Ba, $^{152}$Eu
  - Activity? few kBq
  - Sealed/unsealed? sealed