EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Decay spectroscopy of neutron-rich Zn isotopes by total absorption

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Abstract: We propose to investigate the β decay of $^{80-82}$Zn by total absorption spectroscopy using the Lucrecia setup at ISOLDE. The technique will allow us to identify the β-decay feeding to states in the daughter $^{80-82}$Ga nuclei in order to investigate the competition of Gamow-Teller and First-Forbidden transitions, of relevance for nuclear structure and modeling in nuclear astrophysics. Furthermore, the identification of γ-decay cascades from neutron unbound states will address the competition of neutron and γ decay in the ^{78}Ni region, of interest to experimentally constrain (n, γ) rates of astrophysical interest.

Requested shifts: 15 shifts (split into 1 run over 1 year)

1 Physics outline

The regions close to exotic, doubly-magic nuclei are important for nuclear structure studies and nucleosynthesis in astrophysical scenarios. One of the areas of the nuclide chart subject of intense scrutiny is the one around ^{78}Ni, with $Z = 28$ and $N = 50$. Although it is located far from stability, the expectation is that is should be a doubly-magic nucleus, since the shell closures arise from the spin-orbit shell gaps from the proton f orbitals and neutron g orbitals. Nonetheless, monopole drifts have been discussed in neighboring $Z = 29$ Cu isotopes leading to the modification of ground-state configurations [1, 2], which may indicate the erosion of the $Z = 28$ shell gap. Meanwhile, the $N = 50$ gap seems to be more robust in the region [3, 4]. Only recently in-beam γ-ray spectroscopy of ^{78}Ni was performed [5], confirming the magic nature of ^{78}Ni but suggesting the existence of competing spherical and deformed configurations in the region.

One of the important aspects is the strength of the $N = 50$ neutron shell gap and the proton-driven structure close to ^{78}Ni, which affects nuclear lifetimes and β-decay branching ratios. The β-decay properties of neutron-rich zinc isotopes are the subject of this proposal. The β-strength distribution depends on the wave functions of parent and daughter states, the phase space and the β-decay selection rules. Zn isotopes with N$\geq$50 show a competition of allowed Gamow-Teller (GT) and First-Forbidden (FF) transitions, see Figure 1. GT transitions are favoured by selection rules but generally require the transition of deeply bound neutrons to high-energy states in Ga, which reduces the Fermi factor (phase space). On the contrary, FF transitions have much smaller matrix elements but are far more energetic, therefore becoming favoured by the phase space. This interplay implies the population of high-energy, neutron-unbound levels in Ga isotopes beyond $N = 50$ through low-energy GT transitions, thus contributing to the β-delayed neutron emission probabilities (P$_n$) of these nuclides [7, 8, 9]. On the other hand, these states may decay by electromagnetic de-excitation instead of neutron emission. Characterising the competition between the neutron and γ decay channels above neutron separation energy (S$_n$) in neutron-rich nuclei is of importance in nuclear structure and astrophysics, as the partial γ and neutron widths from unbound states, $\Gamma_{\gamma,n}(E_x)$, can be used to constrain (n, γ) reaction rates [10, 11] of r-process nuclei. The electromagnetic decay of neutron-unbound states is usually disregarded.

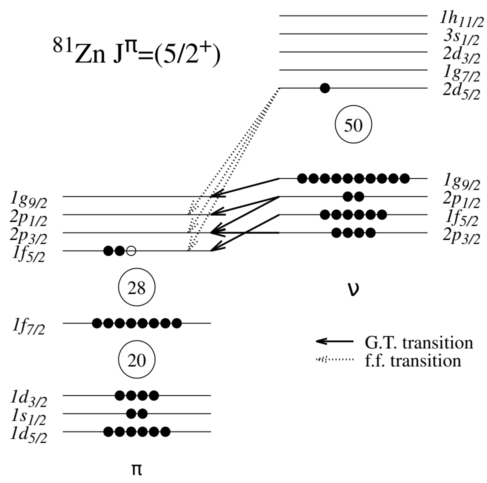

Figure 1: Single-particle orbitals relevant for nuclei around ^{78}Ni. The dots represent the ground-state configuration for ^{81}Zn. GT and FF transitions are schematically represented.

Total absorption γ-ray spectroscopy (TAGS) is the ideal tool to assign the correct β-feeding to excited states, avoiding missing feeding to high-energy levels and misplaced intensities [12]. The high efficiency of the Lucrecia TAS at ISOLDE assures good sensitivity to weak β feeding to high excitation states. This has been proven to be an excellent method to derive the β strength [13, 14]. Here we propose to address the decays of ^{80}Zn, ^{81}Zn and ^{82}Zn. High-resolution data, which is required for a high-sensitivity analysis of the TAS experiment, already exists [15, 16, 17] for these decays. The measurement of ^{80}Zn and ^{81}Zn β decays has recently been performed at ISOLDE. In the latter [16], the measured direct β feeding to the ^{81}Ga ground state and the P_n probability for the decay of ^{81}Zn are at odds with previous studies [18], which illustrates the risk of using apparent β-feeding intensities obtained by high-resolution γ spectroscopy. For the ^{82}Zn decay [17], the data was obtained at HRIBF, although the decay has also been observed at ISOLDE in the framework of experiment IS441. The P_n values of interest quoted in Table 1 are from these references but they have recently been measured with higher precision using neutron counting by the BRIKEN collaboration [19].

2 Goals of the proposal

The aim of the present proposal is twofold. Firstly, we aim to study the competition between allowed GT and FF transitions beyond ^{78}Ni, including accurate measurements of g.s. feedings; and secondly, we will study the competition between γ and neutron emission from unbound states to constrain (n, γ) rates beyond ^{78}Ni.

2.1 Gamow-Teller and First-Forbidden transitions around ^{78}Ni

The β-decay process, typically calculated by considering allowed GT transitions, plays an important role in nuclear physics and astrophysics, specifically in explosive scenarios leading to r-process nucleosynthesis. FF transitions become significant for medium and heavy neutron-rich nuclei due to phase space and nuclear structure reasons [7, 8, 9]. The region above ^{78}Ni is particularly interesting from this viewpoint. One of the most favourable cases here is the decay of Zn isotopes to Ga, and specifically the ^{81}Zn $\rightarrow$ ^{81}Ga decay into the N=50 nucleus ^{81}Ga. The mapping of the feeding to the odd-odd N=49 ^{80}Ga and to the N=51 ^{82}Ga nuclides is also important to understand the role of core-excitations and proton configurations in this region. TAGS spectroscopy is ideal to detect summed γ-ray cascades and identify the β-decay feeding to high-lying states, which otherwise is misidentified as population to lower-lying states via FF transitions.

The ^{80}Zn β decay feeds positive-parity states in ^{80}Ga that have been observed down to relatively low energies, including the lowest-lying 18-ns 1^+ isomer at 708 keV [15]. Negative-parity states are not likely to be fed in this case, since the ground and lowest-lying states are the $3^-{-}6^-$ members of the $\pi f_{5/2}\,\nu g_{9/2}$ multiplet, and other negative-parity states are interleaved with positive parity ones and the ground state.

The allowed GT β decay from the ^{81}Zn ground-state neutron $\nu(d_{5/2})$ or $\nu(s_{1/2})$ configuration populates high-energy states in the ^{81}Ga daughter, since low-lying positive-parity states do not exist. These must originate from the coupling of the odd proton orbitals ($p_{3/2}$, $f_{5/2}$ and $p_{1/2}$) to neutron particle-hole states, therefore implying the breaking of a neutron pair inside the $N = 50$ shell. These core-breaking states give an idea of the magnitude of the $N = 50$ shell gap [20, 18]. The GT β decays to these states must arise from the decay of deeply bound neutrons in ^{81}Zn in the f and p orbitals, with a small Fermi factor, but with sufficient strength compared to FF transitions. The relatively large P_n value measured [16] suggests a significant role of such allowed β transitions to high-lying states above S_n in ^{81}Ga. It should be noted that this situation is similar for other $N = 50$ isotones, for instance the β decay of ^{83}Ge [20]. The role of FF transitions to low-lying negative-parity states in ^{81}Ga seems not as relevant as previously proposed, but high-resolution methods are exhausted and a total absorption measurement is required.

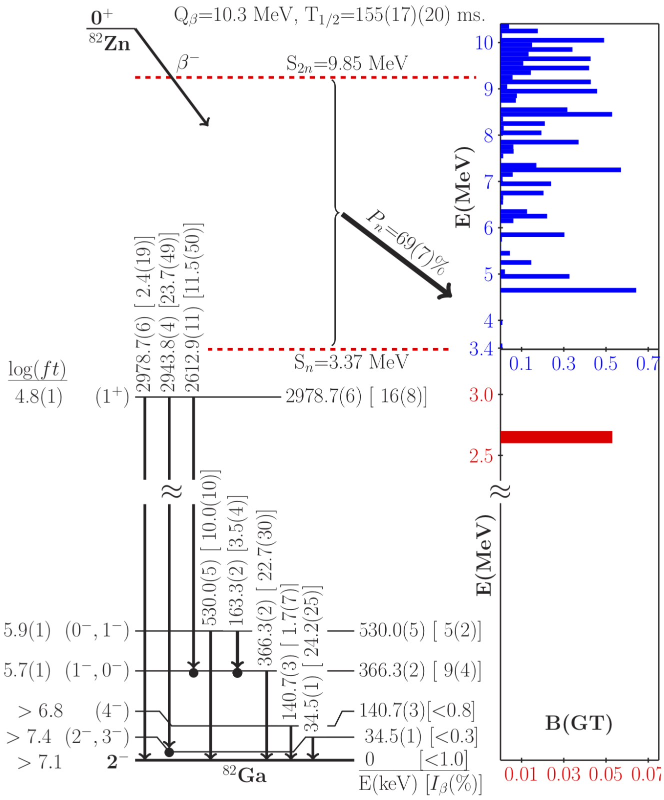

Figure 2: ^{82}Zn decay to ^{82}Ga, taken from [17].

Concerning the decay of ^{82}Zn (Figure 2), the 0^+ ground state would decay to the ^{82}Ga (2^-) state via a FF unique transition, which is very suppressed. Only one 1^+ state fed by GT decay at 2979 keV has been proposed in ^{82}Ga, while most of the intensity is expected above S_n (P_n=68(7)%). Only the neutron orbitals below the $N = 50$ shell closure can produce this state in ^{82}Ga at sufficiently low energy. FF transitions at low energy are also proposed, and apparent direct feeding of the 90-ns 4^- isomer at 141 keV is also observed. A total absorption measurement will help clarify the feeding pattern.

A related aspect to the previously discussed β feeding is the direct ground-state feeding, which is specially relevant for the decay of the odd ^{81}Zn to the $N = 50$ ^{81}Ga isotope, whose g.s. spin-parity has been established as $5/2^-$ from collinear laser spectroscopy [21]. Positive-parity states with either $\nu s_{1/2}$ or $\nu d_{5/2}$ single-particle character have been proposed for ^{81}Zn, leading to a FF decay from the $5/2^+$ to $5/2^-$, or a FF unique decay from $1/2^+$ to $5/2^-$. The apparent β feeding measured in high-resolution γ spectroscopy does not allow for an unambiguous assignment [16]. On the contrary, the total absorption technique proposed here allows for the determination of the g.s. β feeding by means of both the normal TAGS spectrum deconvolution and the $\beta\gamma$ counting method recently developed by Guadilla *et al.* [23], which is an extension of the method initially proposed by Greenwood [22] to β-delayed neutron emitters. The direct β feeding to the g.s. affects the β strength, but also the P_n values obtained from γ-ray spectroscopyby by scaling of β and β-n daughter decays.

2.2 Competition of γ and neutron emission

The competition of γ-ray decay with direct neutron emission from unbound states in exotic nuclei has been documented for a few cases (see eg. [26]). The emission of neutrons above the S_n threshold can be hindered by the angular momentum barrier and therefore large spin changes should be expected between parent and β_n-fed states. In addition, the nuclear structure and selection rules in β decay may play a role in the competition of neutron and γ decay. It is nevertheless usually assumed that neutron decay dominates for β-fed nuclear states above S_n and this is how it is considered in many theoretical calculations. It has been pointed out that the decay of neutron-unbound states by γ rays may have a sizeable impact in astrophysical scenarios [24, 25]. On the other hand, of the nuclear input parameters needed in reaction network calculations for the r-process, neutron-capture (n, γ) rates of very neutron-rich nuclei are the most difficult to obtain experimentally as no radioactive targets or beams with enough intensity are presently available. Here we propose to exploit our total-absorption γ spectroscopy measurement as described by Refs. [10, 11] to help constraining the theoretical predictions obtained from the Hauser-Feshbach statistical model [27]. The identification of γ-decaying neutron-unbound states is therefore of high importance and, presently, there is no better suited tool to tackle this issue than TAGS spectroscopy. Such studies have already been performed [26, 28, 11, 29]. In the case of the neutron-rich Zn isotopes, the region is yet to be explored with total absorption techniques. High-resolution data exists: the three-proton nucleus ^{81}Ga level scheme has recently been expanded [16] with γ transitions up to 6.5 MeV, exhausting the Q_β window up to the S_n value [30]. The available window for the decay of ^{82}Zn is also very large, with Q_β=10.63 MeV [30]. Here, the neutron separation energy of the daughter nucleus ^{81}Ga (S_n=3.37 MeV) is only 400 keV above the strongly fed 1^+ state at 2.98 MeV [17]. Hence, very strong feeding is expected at higher energies.

3 Experimental details

The high purity and intensity of the Zn beams delivered by the ISOLDE facility make it possible to obtain high-sensitivity data for β-decay studies. Examples are provided in [15, 16]. The level schemes of ^{81}Ga and ^{80}Ga are described with sufficient detail in the latter references. High-resolution data for the decay of ^{82}Zn to ^{82}Ga exists [17] too.

The proposed setup is the Lucrecia TAS spectrometer installed at ISOLDE, consisting of a large NaI cylindrical crystal 38 cm in height and diameter, with photopeak efficiency for 1 MeV γ rays of 89% and 79 % for 5 MeV γ-rays. A plastic detector for β-particle coincidence will be used. In addition a germanium telescope detector is used for the detection of low energy γ rays [31]. A tape-driven system, presently under development, will also be used. The short-lived species will be implanted inside the spectrometer to avoid decay losses. A set of collimators and slits is already existing to avoid the accumulation of long-lived activities in the spectrometer.

In nuclei with large P_n values, the γ background coming from the inelastic and capture reactions of the β-delayed neutrons on the TAS material is known to pose a challenge. This is the case of ^{81}Zn and ^{82}Zn (see Table 1). We plan to benefit from the good time resolution of the plastic and TAS detectors to separate (prompt and neutron-delayed)

γ rays from neutron interactions, as indicated in Ref. [29]. Additionally, the technique described in Ref. [28] can be applied. It combines the measured TAS γ spectrum with the β_n-daughter γ-feeding pattern to extract schematic yet valuable information on the β-delayed neutron energy spectrum using simulations of the neutron interactions with the TAS detector. Luckily γ-rays in the β-n daughters have been measured both for ^{81}Zn [?] and ^{82}Zn [17].

4 Yields and beam time request

Table 1 compiles the basic information on the requested ion beams, the daughter isotopes and the possible contaminants. The selectivity and efficiency for the production of Zn ion beams was optimized in Ref. [32] and successfully used in Refs. [15, 16]. We request the use of a UC_2/graphite target equipped with a neutron converter with a temperature-controlled quartz glass transfer line. The ISOLDE Resonance Ionization Laser Ion Source (RILIS) [33] is requested for ionization.
The use of the quartz transfer line suppresses surface-ionized Ga and strongly reduces Rb isobar contamination. In Ref. [16], the ^{81}Rb beam content amounts to 80% of the $A = 81$ beam, but owing to the much longer Rb half-life its activity was negligible. For ^{82}Zn the presence of Rb contamination needs to be assessed. Given that a mass resolution of $\sim$2250 is needed to separate ^{82}Zn and ^{82}Rb the use of the high resolution mass separator may be beneficial.

Table 1: Isotope properties of Zn, Ga and Rb [16, 34] and expected production yields [32]

Nuclide	$T_{1/2}$ (ms)	ABRABLA	Exp. yield/μC	Q_β (keV)	$Q_{\beta n}$ (keV)	P_n (%)
^{80}Zn	562(3)	1.40E+05	1.0E+04	7575(4)	2828(3)	$\sim$1
^{81}Zn	290(4)	2.50E+03	6.0E+02	11428(6)	4953(6)	23(4)
^{82}Zn	155(26)	—	$\sim$1.5E+01	10617(4)	7243(4)	69(7)
Nuclide	$T_{1/2}$ (ms)	ABRABLA	DB yield / μC	Q_β (keV)	$Q_{\beta n}$ (keV)	P_n (%)
^{80}Ga	1900(100)	1.80E+07	6.7E+04	10312(4)	2230(40)	0.9
^{81}Ga	1217(5)	5.80E+06	7.9E+03	8664(4)	3836(4)	12
^{82}Ga	599(2)	3.30E+05	1.8E+03	12484(3)	5290(3)	20
Nuclide	$T_{1/2}$ (min)	ABRABLA	DB yield / μC	Q_{EC} (keV)		
^{80}Rb	0.557(12)	1.60E+08	1.1E+05	5718(2)		
^{81}Rb	30.5(3) / 274.3(2)	5.70E+08	1.7E+05	2240(5)		
^{82}Rb	1.2575(2) / 388.3(4)	1.1E+09	4.50E+06	4404(3)		

The yields for Zn isotopes are based on data acquired under similar conditions during experiment IS441, which are consistent with the ISOLDE yield data-base values. For the beam-time estimates, an average 2 μA intensity is used. A conservative value of 70% transmission to Lucrecia is employed, which accounts both for beam transport and collimation losses. The γ and β detection efficiencies were assumed to be 80% and 40%, respectively. In addition to the decays under investigation, the daughter decays and the contaminants need to be measured under the same conditions. This can be performed by adapting the proton sequence in the supercycle and the measurement cycles. For ^{80}Zn and ^{81}Zn, 1 and 2 shifts, respectively, are needed to achieve more than 10 million $\beta\gamma$ coincidences, while 1 more shift is needed for background and daughter activity measurements. In the case of ^{82}Zn, 8 shifts are required to achieve about 500 kcounts in the $\beta\gamma$ spectrum. The daughter activity can be measured during the same collection time. Two extra shifts for background measurement and RILIS off data taking are also required in this case. In addition, 1 shift is requested to tune the quartz transfer line.

Summary of requested shifts: We request a total of 15 shifts, 1 for optimization of the transfer line, 1 shift for $A = 80$, 3 shifts for $A = 81$ and 10 shifts for $A = 82$.

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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 by update of the tape station
[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 experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum	high vacuum 10^{-6} mbar		
Temperature	LN_2 77 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)	Zn		
Beam intensity	20000 s^{-1}		

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	10 kBq		
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]