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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Neutron transfer on the intruder ^{79}Zn isomer to probe the $N = 50$ shell gap in ^{80}Zn

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Abstract:

Shape coexistence around ^{78}Ni is key to understanding shell evolution around one of the most neutron-rich doubly-magic nucleus known. The reduction of the $N = 50$ gap from $Z = 40$ to $Z = 32$ and the appearance of low-lying, deformed, intruder states close to $Z = 28$ makes it necessary to probe the evolution of the gap as well as of the intruder configurations in ^{80}Zn, only two protons above the ^{78}Ni core. We propose to perform a (d,p) neutron transfer on the ground $9/2^+$ and isomeric $1/2^+$ states of a ^{79}Zn beam. The exclusive differential cross sections to the states of interest in ^{80}Zn will be measured in the ISS setup. We foresee to obtain the energy of the $5^+, 6^+$ states, which are built by breaking the shell gap, as well as of the intruder 0^+_2 state. Its overlap with the ^{79}Zn $1/2^+$ intruder isomer will provide crucial information on the wave function of deformed configurations in this region.

Summary of requested shifts: 21 shifts + 3 shifts for ISS setup

1 Physics Motivation

The first spectroscopy study of the doubly-magic ^{78}Ni isotope pointed out one of the main issues found investigating the $N = 50$ isotonic chain from $Z = 40$ to $Z = 28$: the appearance of intruder, deformed configurations at low energy, pointing to shape coexistence [1, 2, 3]. Indeed, the $N = 49$ isotones offer a paradigmatic example of the lowering in energy of intruder configurations next to a shell closure. Along the isotonic chain, $1/2^+$ and $5/2^+$ states appear at low energies, as shown in Fig. 1: they are *a-priori* one particle-two holes (1p-2h) excitations across the $N = 50$ gap from the $\nu g_{9/2}$ to the $\nu s_{1/2} d_{5/2}$ shells above the shell closure [4]. Their rapid lowering in energy from about 1.5 MeV in ^{87}Sr to only $\sim$ 500 keV in ^{81}Ge, and their re-increasing to $\sim$ 950 keV in ^{79}Zn, has been interpreted as the conventional behaviour of intruder states which ought to have a minimum in energy at the mid of the proton shell $Z = 28 - 40$ due to the increase of quadrupole correlations [4]. A recent work proposed that the $1/2^+$ isomer in ^{79}Zn is the bandhead of a deformed $K = 1/2$ intruder band, to which also the other intruder state $5/2^+$ belongs [9].

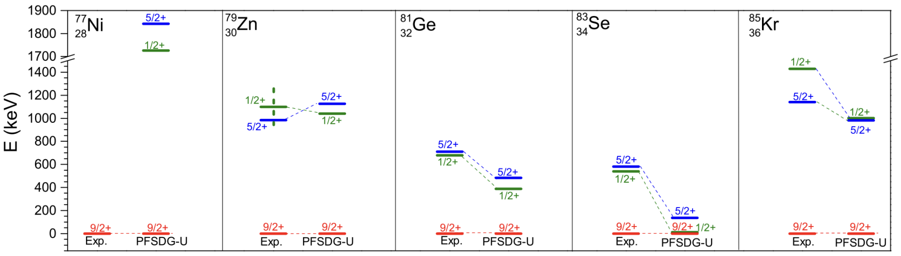

Figure 1: The intruder states in $N = 49$ isotpnes. Picture from Ref. [4].

Intruder 2p-2h 0^+ states are predicted also in the $N = 50$ nuclei [5]. Even if several excited 0^+ states are known in ^{88}Sr, ^{86}Kr and ^{84}Se, tentatively also in ^{82}Ge, their experimental identification as intruder 2p-2h states is often uncertain. In any case, the yrare 0^+ levels do feature a decrease in energy towards the mid proton shell at $Z = 34 - 32$.
The $N = 50$ shell closure was also probed with mass measurements which have shown that the $\nu g_{9/2} - d_{5/2}$ gap has a parabolic behaviour with a minimum at $Z = 32$ and a re-increase in ^{80}Zn [6]. The size of the $N = 50$ gap can also be studied measuring the energy of the excited states which represent a breaking of the shell, namely $5^+, 6^+$ and $13/2^+$ states in even and odd $N = 50$ isotones, respectively [7]. The energy of these states, known until $Z = 31$ in ^{81}Ga, shows that the shell-gap decreases in agreement with the mass measurements, but no re-increase is spotted in ^{81}Ga, towards $Z = 30$ [7], as shown in Fig. 2.

Considering the state of the present knowledge of nuclear structure in the ^{78}Ni region, it is clear that spectroscopy of medium-spin and intruder states in ^{80}Zn is much needed. Only the yrast 2^+, 4^+ levels are known, with with only a few other observed states having an uncertain spin assignment [12, 13]. The energy of the $5^+, 6^+$ states will allow one to probe the $N = 50$ gap, while the energy of the intruder 0^+ state(s) (at least the yrare 0^+_2) will help to understand how the quadrupole correlations are impacting nuclear structure when approaching $Z = 28$. The nature of the wave function of the intruder 0^+_2 state in ^{80}Zn is interwinded with another major spectroscopic feature of this region: the rapid lowering in energy of the $\nu s_{1/2}$ shell above $N = 50$ from $Z = 40$ to $Z = 32$: at $Z = 30$ it should be almost degenerate with the $\nu d_{5/2}$ shell [8]. This, in turn, brings up a question: is the intruder yrare 0^+_2 state in ^{80}Zn a 2p-2h

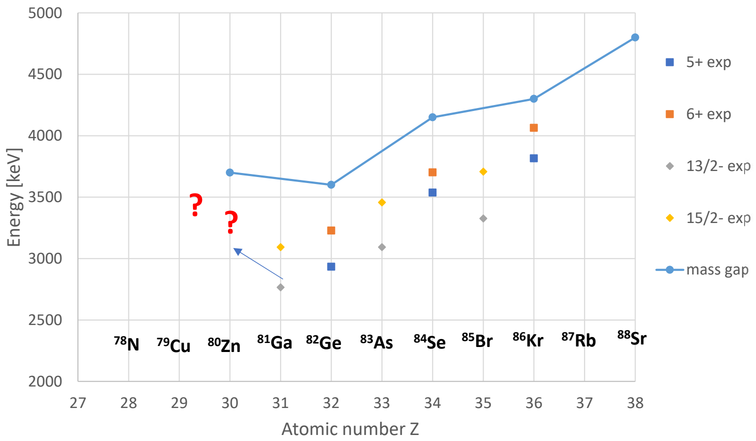

Figure 2: Evolution of the $N = 50$ shell gap from mass measurements as well as spectroscopic data. The position of the $N = 50$ core-breaking states in ^{80}Zn is not known.

neutron excitation of the type $(g_{9/2})^{-2} - (d_{5/2})^2$ or $(g_{9/2})^{-2} - (s_{1/2})^2$ or some mixing of the two configurations? The answer to this bears crucial information on the deformation of the intruder states towards ^{78}Ni itself, where the degeneracy of the $\nu d_{5/2}$ and $\nu s_{1/2}$ shells should be more marked, with the possibility even of an inversion [8]. Laser spectroscopy assigned to the ^{79}Zn $1/2^+$ intruder isomer a main $\nu(g_{9/2})^{-2}(s_{1/2})^1$ component through the g-factor measurement [2]. From a naive shell-model point-of-view it is then expected that adding a neutron to this state will create an intruder 0^+ in ^{80}Zn with a dominant $\nu(g_{9/2})^{-2}(s_{1/2})^2$ wave function. In the calculations presented in Ref. [9], the $1/2^+$ and $5/2^+$ states in ^{79}Zn feature a quite mixed *gds* wave function, although with a predominance of the $\nu s_{1/2}$ component for the $1/2^+$ state, predicted with a deformation of $\beta = 0.22$, compatible with the isomer shift [2]. The 0_2^+ state in ^{80}Zn has a predicted similar mixing of different shells above $N = 50$ in its wave function; its deformation is calculated of the same magnitude of the ^{79}Zn intruder states [9].

The aim here is to study these aspects at the same time with a direct neutron transfer measurement ^{79}Zn$^{gs,1/2^+}$(d,p)^{80}Zn. We will take advantage of the fact that in ^{79}Zn the intruder 1p-2h $1/2^+$ state is a long-living isomer, and thus the ISOLDE ^{79}Zn beam is composed of both the ground state and the isomeric state [2, 9]. The transfer on the ^{79}Zn $9/2^+$ ground state will allow one to populate the ^{80}Zn $5^+, 6^+$ states with favored $\ell = 0, 2$ transfers, while the (d,p) reaction on the ^{79}Zn $1/2^+$ intruder isomeric state will have a large cross section for the population of the intruder 0_2^+ state in ^{80}Zn with an $\ell = 0$ transfer. Figure 3 presents a schematic view of the shell-model structures involved in the neutron transfers on the two ^{79}Zn states composing the ^{79}Zn ISOLDE beam.

1.1 ^{79}Zn Coulex at Miniball

The Coulomb excitation of a ^{79}Zn$^{gs,1/2^+}$ beam was successfully performed at Miniball during the run IS646 [10]. Figure 4 shows the spectrum and the deduced ^{79}Zn partial level scheme resulting from Coulomb excitation from both the ground state and the $1/2^+$ isomer. A previous β-decay work already built a level scheme on top of the $1/2^+$ level, finding almost no connecting transitions between the ground state and intruder isomer bands [11]. The preliminary results

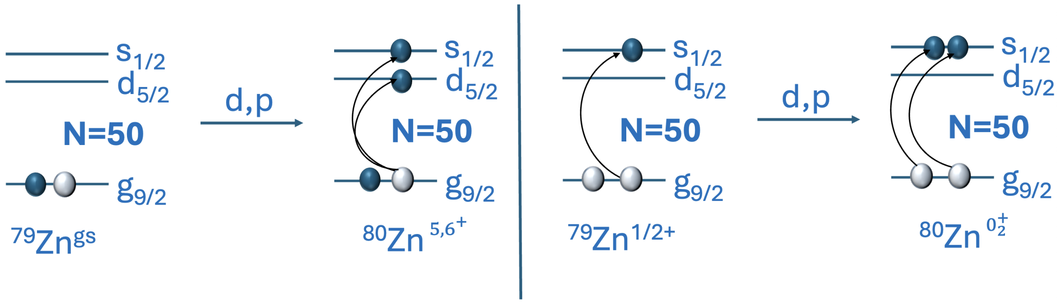

Figure 3: Schematic shell-model view of the proposed reaction(s). The left panel shows the neutron transfer on the ^{79}Zn ground state to the predicted 5^+,6^+ states in ^{80}Zn. The right panel shows the transfer from the ^{79}Zn intruder isomeric $1/2^+$ state to the predicted intruder 2p-2h 0^+_2 in ^{80}Zn. Only the main wave function components are illustrated.

from IS646 show a large $E2$ strength built on the $1/2^+$ state, also connecting it to the other intruder $5/2^+$ state, suggesting a significant mixing between the $s_{1/2}$ and $d_{5/2}$ wave functions. The proposed neutron transfer measurement will help to clarify this aspect, probing the amount of $\ell = 0$ transfer to the intruder 0^+_2 level in ^{80}Zn.

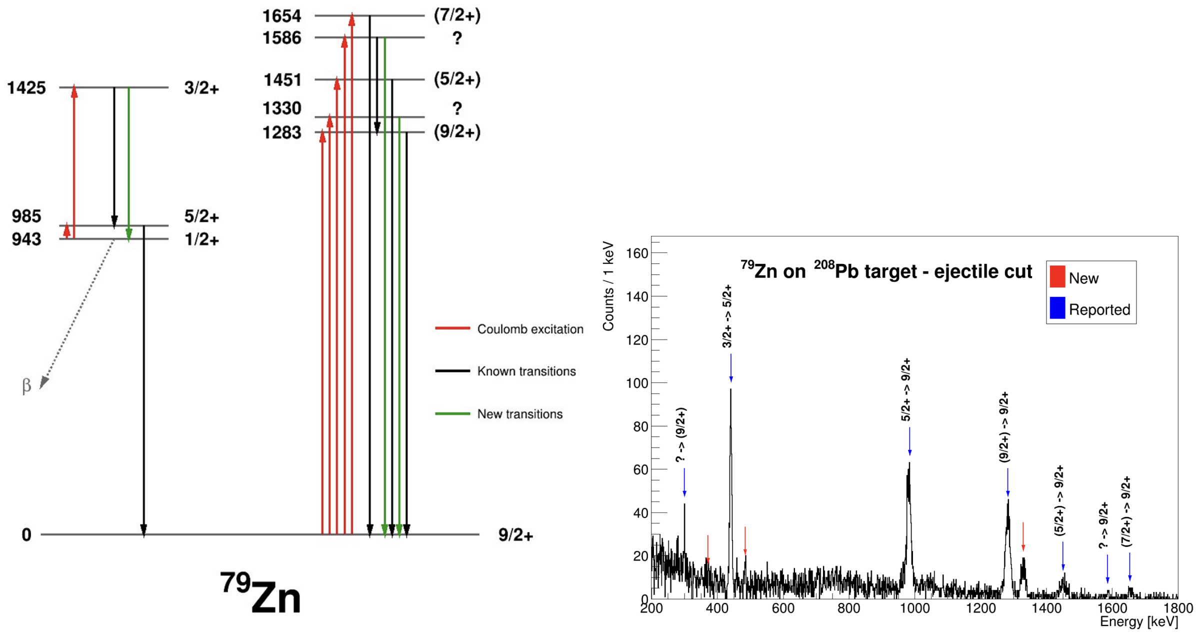

Figure 4: On the left: Coulomb excitations and γ-ray transitions observed during the ^{79}Zn Coulex experiment at ISOLDE. On the right: γ-ray spectrum measured by Miniball during the ^{79}Zn Coulex run.

2 Proposed measurement

The intruder $1/2^+$ state in ^{79}Zn is a long living isomer which is about 7% of the total ISOLDE ^{79}Zn beam [9, 10]. In the recent Coulex experiment IS646, a ^{79}Zn accelerated beam intensity of about $8{\cdot}10^4$ pps was obtained [10]. We plan to use the ISS device to measure the differential cross section of the $^{79}\mathrm{Zn}^{gs,1/2^+}$(d,p) reaction to the different excited states of ^{80}Zn.
The ^{80}Zn excited states as well as the predicted spectroscopic factors were calculated using an interaction derived from the the GWB Hamiltonian from the Oxbash library. The interaction has a ^{66}Ni core and comprises as active shells the full *gds* neutron space across $N = 50$ as well as the $f_{5/2}p_{3/2}p_{1/2}$ shells between $Z = 28$ and $Z = 40$. This interaction can reproduce the intruder states along the $N = 49$ isotonic chain, the $2^+, 4^+, 5^+, 6^+$ energy and $B(E2)$ along the lower-mass $N = 50$ isotones. The ^{79,80}Zn state energies and the (d,p) spectroscopic factors were obtained from a diagonalization with the Antoine code, allowing up to 4p-4h excitations across $N = 50$. In general, the results are qualitatively similar to the interaction in Ref. [9]. The wave functions of the 0_2^+ [1] and $5_{1,2}^+, 6_1^+$ states in ^{80}Zn are constituted by about two and one neutron holes in the $g_{9/2}$ shell, respectively. The missing neutrons are excited mainly to the *sd* shells above $N = 50$. Similarly to the calculations in Ref. [9], the breaking of the $N = 50$ core also implies a change in the protons wave function above $Z = 28$, with a small depletion of the $\pi f_{5/2}$ shell and more protons in the $\pi p_{3/2}, p_{1/2}$ shells, compared to the spherical ground state.
The calculated spectroscopic factors were then used as a basis for DWBA calculations with the FRESCO code. The obtained differential cross sections were in turn used for the experiment simulation using the NPTOOL software. Table 1 shows a summary of the predicted cross sections and counting rates for the excited states of ^{80}Zn we will populate with a significant yield. The final rates includes the ISS response function. The DWBA calculations were performed at different beam energies, from 4 MeV/u to 10 MeV/u, and the best rates are obtained at a beam energy of 6 MeV/u. The CD_2 target thickness is a compromise between excitation energy resolution and statistics, which in our case works out at 300 μg/cm^2.

^{80}Zn state	Excitation Energy (MeV)	Transferred ℓ	SF	Beam pps	σ (mb)	ISS counts per shift	ISS counts 21 shifts
5_1^+	3.0	0 2	0.1 0.7	$^{79}\mathrm{Zn}^{gs}$ $7.4{\cdot}10^4$	1.2 1.3	36	750
6_1^+	3.2	0	0.3	$^{79}\mathrm{Zn}^{gs}$ $7.4{\cdot}10^4$	2.5	35	740
5_2^+	3.6	2	0.8	$^{79}\mathrm{Zn}^{gs}$ $7.4{\cdot}10^4$	0.7	10	220
0_2^+	2.2	0	0.4	$^{79}\mathrm{Zn}^{1/2^+}$ $5.6{\cdot}10^3$	1.6	2	40

Table 1: Estimation of collected statistics for a $^{79}\mathrm{Zn}^{gs,1/2^+}$ beam at 6 MeV/u and an intensity of $8{\cdot}10^4$ pps. All other ^{80}Zn states are predicted to have negligible cross sections. Predictions on spectroscopic factors (SF) are based on a shell model allowing up to 4p-4h across $N = 50$.

In Fig. 5 we present the predicted differential cross sections compared with the ISS angular

[1] The $N = 50$ gap was tuned to reproduce the 0_2^+ energy calculated in Ref. [9].

coverage in a configuration where the target to array distance is (-80—580mm) and field settings is 2T. The angular coverage is sufficient to sufficient to differentiate the different transferred angular momenta.

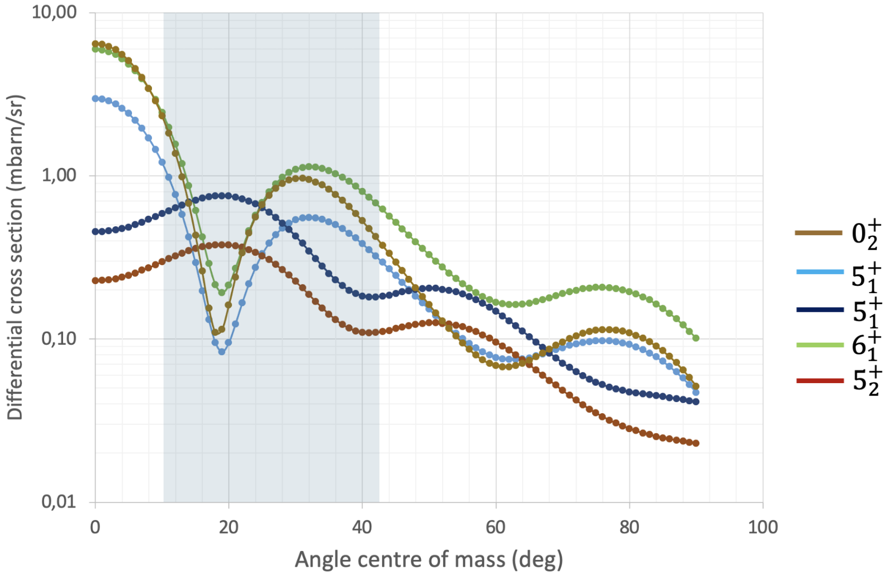

Figure 5: Predicted differential cross section for a DWBA calculation performed with the FRESCO code. The shaded are is the ISS angular coverage in the configuration described in the text.

Figure 6 presents the output of the Monte Carlo simulation for particle spectroscopy in ISS. The $5_1^+, 6_1^+$ levels are not well separated, while the 5_2^+ is clearly distinguished. Since the two 5^+, 6^+ levels represent both a break of the $N = 50$ core and their predicted energy is anyway within the uncertainties of the shell model, their resolution is not crucial for the measurement. The intruder 0_2^+ state clearly stands out: the low percentage of ^{79}Zn in the isomeric state is counterbalanced by a relatively large cross section for the $\ell = 0$ transfer.

Finally, we foresee the use of the zero-degree ionization chamber to check beam contamination and clean the fusion-evaporation background. In the previous IS646 run with ^{79}Zn beam we observed only a minor contamination of the order of 2% from a higher Z, likely Kr.

In total 21 shifts are requested to gather the required statistics, plus 3 shifts for ISS setup.

References

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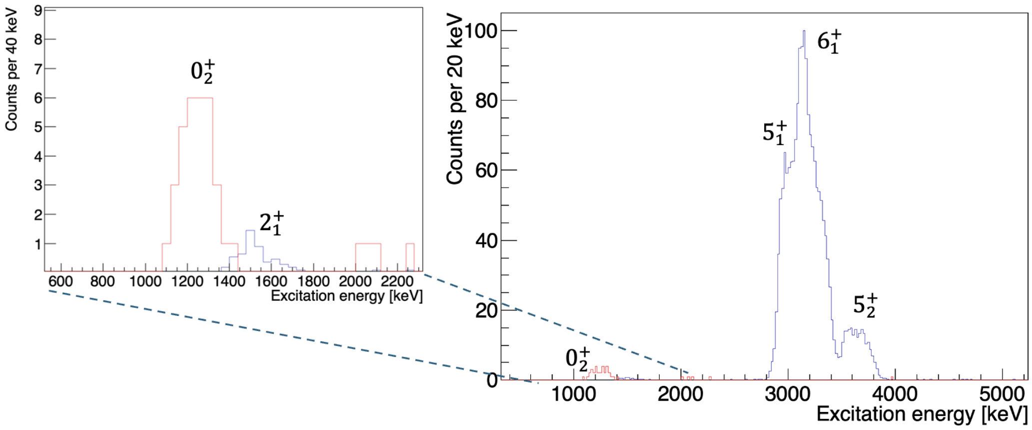

Figure 6: Simulation of the excitation energy spectrum in ISS. The blue line represents transfer on the ^{79}Zn ground state, while the red line transfer on the ^{79}Zn $1/2^+$ isomer. The right panel show the $5_1^+, 6_1^+$ states not well resolved, and the 5_2^+ level resolved. The left panel shows, in red, a zoom in the low energy region where the peak corresponding to the predicted intruder 0_2^+ state is simulated. Predicted at 2.1 MeV, it appears at 1.2 MeV because the excitation energy has been determined assuming transfer from the ^{79}Zn ground state.

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[12] Y. Shiga *et al.*, Phys. Rev. C 93, 024320 (2016)

[13] J. Van de Walle *et al.*, Phys. Rev. Lett. 99, 142501 (2007)

3 Details for the Technical Advisory Committee

3.1 General information

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

- ☒ Permanent ISOLDE setup: *ISS*
  - ☒ 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*

3.2 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 (/μC)	Minimum required rate at experiment (pps)	$t_{1/2}$
Isotope 1 Isotope 2 Isotope 3		$8{\cdot}10^4$	746 ms

- Full reference of yield information (*e.g. yield database, elog entry, previous experiment number, extrapolation and/or justified scaling factors, target number*)
- Target - ion source combination:
- RILIS? (*Yes*)
  - ☐ Special requirements:
- Additional features?
  - ☒ Neutron converter: (*Yes*)
  - ☒ Other: (*quartz transfer line*)
- Expected contaminants: *Isotopes with similar A/q from EBIS, few% of the ^{79}Zn beam*
- Acceptable level of contaminants: (*few% of the ^{79}Zn beam, either stable or radioactive*)
- Can the experiment accept molecular beams? Not relevant
- Are there any potential synergies: IS743 (^{78}Zn beam)

3.3 HIE-ISOLDE

For any inquiries related to this matter, reach out to the ISOLDE machine supervisors (please do not wait until the last minute!).

- HIE ISOLDE Energy: *(∼6 MeV/u);*
  - ☒ Precise energy determination required
  - ☐ Requires stable beam from REX-EBIS for calibration/setup? *Isotope?*
- REX-EBIS timing
  - ☒ Slow extraction
  - ☐ Other timing requests
- Which beam diagnostics are available in the setup? Ionization chamber
- What is the vacuum level achievable in your setup?

3.4 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: 21 shifts of ^{79}Zn

With protons	Requested shifts
Yield measurement of isotope 1 Optimization of experimental setup using isotope 2 Data taking, isotope 1 Data taking, isotope 2 Data taking, isotope 3 Calibration using isotope 4	
Without protons	Requested shifts
Stable beam from REX-EBIS (after run) Background measurement	

3.5 Health, Safety and Environmental aspects

3.5.1 Radiation Protection

- If radioactive sources are required:
  - Purpose?
  - Isotopic composition?
  - Activity?
  - Sealed/unsealed?
- For collections:
  - Number of samples?
  - Activity/atoms implanted per sample?
  - Post-collection activities? (*handling, measurements, shipping, etc.*)

3.5.2 Only for traveling setups

- Design and manufacturing
  - ☒ Consists of standard equipment supplied by a manufacturer
  - ☐ CERN/collaboration responsible for the design and/or manufacturing
- Describe the hazards generated by the experiment:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]

Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			