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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Cu decay into neutron-rich Zn isotopes: shell structure near ^{78}Ni

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Abstract: With only two protons above nickel, Z = 28 shell closure, and the increasing occupation of neutrons in the $1g_{9/2}$ orbital, neutron-rich Zn isotopes are ideally suited to study the evolution of the proton shell gap and the stability of the neutron shell gap, N = 50, near the double magic ^{78}Ni. In addition, the zinc isotopes are also an excellent probe to test Large-Scale Shell-Model calculations. The limited knowledge of several properties of zinc isotopes does not permit yet to fully understand not only the zinc chain, but also the most exotic neutron-rich nickel isotopes. We propose to study the β decay of copper isotopes into Zn, masses A = 74 to A = 79, in order to clarify and expand the level scheme and measure lifetimes of low-lying transitions. This new information will shed light on the evolution of the collectivity approaching the N= 50 shell closure. In addition, we would also like to investigate the production of ^{80}Cu for future proposals, making use of the unique purity and intensity of ISOLDE beams. The experiment will be performed with the ISOLDE Decay Station (IDS) setup equipped with 4 Clover Germanium detectors, 2 $LaBr_3$(Ce) detectors, a fast plastic detector and in combination with the tape station.

Requested shifts: 26 shifts (split into 1 runs over 1 year)

1 Introduction

One of the main cornerstones of the Nuclear Shell Model are the so called magic numbers. Nuclei possessing a doubly magic number of nucleons (both protons and neutrons) present much higher nuclear binding energy than their neighboring nuclei due to the particle filling complete shells. This model is able to accurately predict the properties of nuclei along the valley of stability, but recent experimental results have shown that when we move towards the neutron-drip line the nuclear shells rearrange, giving rise to new magic numbers and the possible disappearance of conventional ones. For example N = 32 has been proposed to be a magic number for ^{52}Ca [1] and N = 34 for ^{54}Ca [2]. But the picture is far from clear, as the magicity of ^{52}Ca has been recently challenged by *Garcia-Ruiz et al.* [3] in a laser spectroscopy experiment. It is, thus, of paramount importance to study the doubly-magic nuclei far from stability to test the validity of the model.
Nickel isotopes are the ideal laboratory to study the evolution of magic numbers as a function of the neutron-to-proton ratio, as well as a perfect test for the different Shell Model calculations. These isotopes are the only ones in the nuclear chart to have three different conventional doubly-magic nuclei, from the most neutron-deficient ($^{48}_{20}$Ni$_{28}$ N/Z $\sim$ 0.7 [4]), the nucleus with the highest binding energy per nucleon ($^{56}_{28}$Ni$_{28}$), to the most neutron-rich one ($^{78}_{50}$Ni$_{28}$ N/Z $\sim$ 1.8 [5]), plus the non-conventional harmonic-oscillator sub-shell closure N = 40 ($^{68}_{40}$Ni$_{28}$ [6]).
The ^{78}Ni nucleus has attracted much attention in the last years, both from an experimental [5, 7, 8] and a theoretical [9, 10] point of view, but despite the effort, no direct evidence

of its doubly magicity has been found. Moreover, very recent experiments [11, 12] point out to the existence of shape coexistence at low energies just above ^{78}Ni, something that is not expected to happen near doubly-magic nuclei. Once again, we can see that the picture of doubly-magic nuclei with extreme neutron-to-proton ratios is not clear and more experimental information is needed to understand the nuclear structure of the region.

Unfortunately, the most neutron-rich ^{78}Ni and the nuclei below it are currently out of reach of the present generation ISOL facilities, so to study the region we must search for information on the neighboring nuclei above it. With two protons above the Z = 28 gap and the increasing occupation of neutrons in the $1g_{9/2}$ orbital, zinc isotopes are ideally suited to study the evolution of the Z = 28 shell gap and the stability of the N = 50 neutron shell gap near ^{78}Ni. Moreover, the N = 50 energy gap has been shown to decrease from Z = 40 to Z = 32, to increase again for Z = 31 and 30. If this trend persists, an enhanced N = 50 shell gap energy, relative to the surrounding nuclei, can be expected for ^{78}Ni (Z = 28). This effect has been observed recently in ^{80}Ge by *Gottardo et al.* [11]. Additionally, useful information can be deduced by the study of odd-even isotopes. It is well-known the existence of a strong tensor interaction between the $\nu g_{9/2}$ orbital and the $\pi f_{7/2}$ orbital and pf proton sub-shell ($p_{3/2}$, $f_{5/2}$, $p_{1/2}$). This interaction is attractive between the $\nu g_{9/2}$ and the $\pi f_{5/2}$ single-particle orbit, but repulsive between $\nu g_{9/2}$ and $\pi f_{7/2}$. This interaction causes a reduction on the energy gap between the $\pi f_{5/2}$ and $\pi f_{7/2}$ proton orbitals as neutrons gradually fill the $\nu g_{9/2}$ orbital, with a maximum at $N = 50$ ^{78}Ni [13]. As a consequence, when going toward neutron-richer nuclei, the monopole part of the residual interaction plays a dominant role determining the properties of the quasi-particle states and the interaction among them. An inversion of the $p_{3/2}$ and $f_{5/2}$ proton orbitals was predicted and later observed in ^{75}Cu by *Flanagan et al.* [14]. This orbital inversion has not been confirmed for the Zn isotopes in the region.

This interplay between different closed and open shells also gives rise to the shape-coexistence phenomenon. So far it was believed to happen in specific regions which had a magic number, semimagic number or close to one of them for one of the nucleons but an open shell of the others,at north-east of ^{56}Ni [15]. But very recent laser spectroscopy results [12] have shown the presence of shape coexistence in ^{79}Zn. If the closest odd-Zn nucleus to the doubly-magic ^{78}Ni presents this effect, it can be expected to happen in lighter ones in the mid-shell.

In light of the recent results, it is clear the necessity to investigate and extract new experimental information about the Zn isotopes, this information will prove to be an invaluable input for future Large-Scale Shell-Model calculations and improve our understanding of this particular region of the nuclear chart.

But the interest in the neutron-rich Zn isotopes does not focus only in their nuclear structure. The magicity of N = 50 far from stability plays a crucial role in the rapid neutron-capture (r) process, so it is of great importance in the field of astrophysics. The r-process is assumed to be a extremely fast sequence of neutron captures and β decays, responsible for the nucleo-synthesis of most of the elements heavier than Fe. The r-process path goes through the neutron-rich regions, with the so-called waiting regions (bottle necks) happening at the magic numbers. Thus some of the most important physic parameters for the theoretical model predictions are the β decay, half-lives and the

β-delayed neutron emission branches of the nuclei around the waiting points, such as ^{78}Ni with N = 50. While this nucleus remains inaccessible to ISOL facilities, valuable information can be extracted from neutron-rich Cu beams. The β-n branches for these isotopes present large uncertainties and conflicting measurements, and thus, experiments with Cu beams present a perfect opportunity to measure β-n branches with a very high astrophysical value. Moreover, it has been shown that the neutron-capture rate of ^{78,79}Zn can cause the largest change (at least 15%) in the overall abundance pattern [16], so any information about this nuclei will help constrain the theoretical models.

2 Physics motivation

2.1 Odd-even Zn

Low-energy states in the odd-Zn isotopes contain valuable information on the interplay between single-particle and collective motion. Considering that they are only two protons above ^{78}Ni, the energy systematic of the isomeric levels in the Zn isotopic chain is instructive to study the possible doubly-magic nature of ^{78}Ni. Spin-parity for ground and isomeric states are only tentative for ^{73}Zn and above, with the recent exception of ^{79}Zn [12], see Fig. 1(A). It has to be noted that, with the exception of ^{79}Zn, the ground states of the chain above N = 40 are not suggested to be $9/2^+$, as could be expected from a naive shell-model interpretation. This would indicate that only the one-neutron hole respect to N = 50 can be described in terms of single-particle state, requiring the investigation of collective effects for the lighter nuclei. One of the best probes available to study collectivity in nuclei are the $B(M1)$ and $B(E2)$ values, that can be extracted from half-life measurements, but so far no excited-state lifetime has been measured for the $^{73-79}$Zn isotopes.

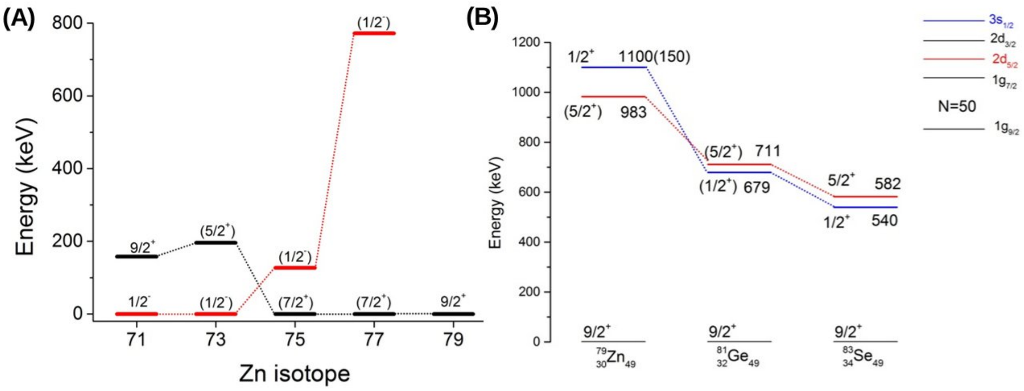

Figure 1: (A) Tentative ground and isomeric states in odd-Zn isotopes. (B) Systematic of the $1/2^+$ isomers along the N = 49 chain.

Focusing on the most interesting case, the ^{79}Zn nucleus, only a handful of levels have been observed in a (d,p) reaction [17], with no β-decay experiment reported so far. An isomeric state has been recently interpreted as a signature of shape-coexistence due to the large radii difference with the g.s. [17, 12]. An undetermined lifetime of a few hundred

miliseconds was proposed in [12] and an energy of 1.10(15) MeV was speculated based in the lack of coincidences between levels in [17] for the A = 79 isomer. This tenuous information on the isomer does not allow to complete the systematic of the (2h-1p) states along the N = 49 isotone chain. For example for Z = 32 and 34 there is an inversion on the excitation of neutrons to the $\nu 2d_{5/2}$ and $\nu 3s_{1/2}$ observed in the reversal of the first $5/2^+$ and $1/2^+$ states (see Fig. 1(B)), linked to the reduction of the N = 50 gap already observed for the Z = 32 - 40 isotopes in the region (see [11] and references within). For ^{79}Zn the first $5/2^+$ is at 983 keV, with the $1/2^+$ isomer proposed at only 1.10(15) MeV (see Fig. 1(B)), with such large uncertainty the order of the levels cannot be firmly established. An inversion of the orbitals so close to the shell gap would challenge the magicity of ^{78}Ni, so precise information about the energy and half-life of this isomer is of paramount importance. We thus propose a systematic study of the isomer states (for which most half-lives are unknown) in the odd-Zn isotopes. Since the level-scheme populated in the neutron-rich Zn ground state decay is precisely known (private communication by *L.M. Fraile*, IS441), it is possible to find γ transitions only populated in the isomer decay and measure the isomeric half-lives.
In summary we propose a systematic study of the collective properties of the neutron-rich Zn isotopes, A = 75,77 and 79, and their isomeric states via a high-selectivity spectroscopy and fast-timing experiment.

2.2 Even-even Zn

In the case of the even-even zinc nuclei, the information about the level scheme and lifetimes are well known up to A = 72. The latest Coulex and Recoil Doppler Shift (RDS) experiments confirm the existence of a maximum in the B($E2$; $2_1^+ \rightarrow 0_1^+$) around ^{72}Zn as well as the evolution of the different levels along the isotopic chain [18, 19]. On the other hand, the disagreement between these techniques becomes evident when the $B(E2;\, 4_1^+ \rightarrow 2_1^+)$ is compared. As it is shown in Fig. 2(A), there are discrepancies between the values obtained via Coulex [20, 21, 22] and RDS [19, 23] techniques.
Unfortunately, this inconsistency continues along the isotopic chain, with no convincing explanation for this issue. The most plausible one is related to the way that the nuclei are excited in each technique: On the case of the RDS experiments only the yrast bands are populated and the feeding coming from the non-yrast bands is neglected. On the other hand, in the multi-step Coulex experiments the yrast and non-yrast bands are populated, and also information of the diagonal matrix elements is extracted. Hence, a full characterization of the nucleus structure is obtained. In contrast, the fast-timing technique [24, 25] provides an independent and direct measurement of the excited-state lifetimes respect to the other techniques mentioned before. This will help us to validate the different interpretation of the shell-model calculations performed until now and also it will provide new information about most exotic even-even nuclei.
Starting from A = 74, the lack of information about spin-parities and sometimes the position of some of the energy levels still persists. During the last years, several experiments have been performed at INFN-LNL. All of them show slightly different energies for the 6^+ state, but in general, the yrast band is mostly well known, [32, 19, 33]. Further away of this band the spin parity of the rest of the levels are unknown, as well as the energy of

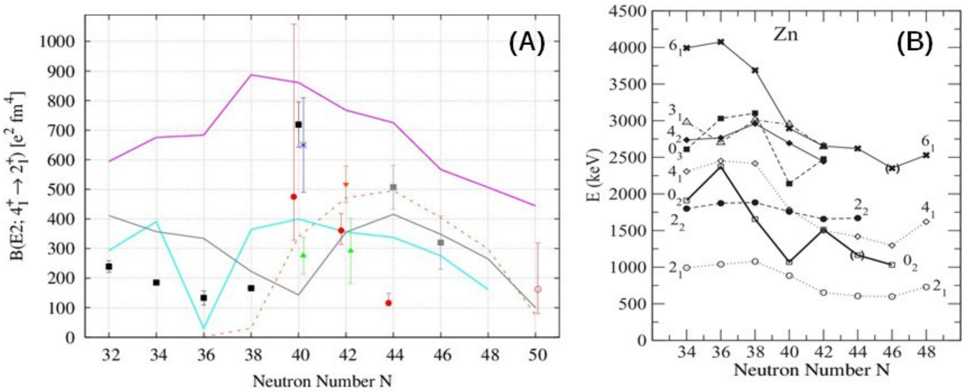

Figure 2: In Fig. (A) the black and gray filled squares are extracted from [26], all of them were obtained using DSAM or COULEX technique, respectively. The blue star is from [22], the orange filled inverted triangle is from [21] , the green filled triangles are from [23], the red filled circles are from [19] and the red open circle is from [27]. The solid lines represents different theoretical calculations i.e.: in light blue using the JUN45 interaction [28], in pink the Gogny D1S force [29], in orange the SM calculation using the LNPS interaction [30] and in gray MCSM [31]. Figure (B) was adapted from [18].

the 0_2^+ state, see Fig. 2(B).
Secondly, in the region of interest, the most exotic nucleus for which excited states lifetimes have directly been measured is ^{74}Zn by *Louchart et al.* using the RDS technique [19]. As it is shown in Fig. 2(A), the two values for the $B(E2;\, 4_1^+ \rightarrow 2_1^+)$ the oldest measured by *Van de Walle et al.* [34] and the newest obtained by *Louchard et al.* [19] are in disagreement. These results are one of the most dissimilar values obtained in this region. As a consequence, this discrepancy has a big impact in the interpretation of the rigidity of this nucleus. For ^{76,78}Zn no lifetime has directly been measured, the only information is from Ref. [34] using the Coulex technique.
Finally, last fall in 2015, the first part of the first HIE-ISOLDE experiment (IS557) was successfully carried out [35]. In this experiment ^{74,76}Zn were studied via Coulex. The β-decay experiment that we propose is also a complementary study of that Coulex experiment. This study will provide independent and new information, which it will be very useful in the analysis of the IS557 experiment. Moreover, the independent information obtained in non-Coulex experiments like branching ratios and lifetimes, provides essential constraints for the GOSIA analysis, as it is well explained in the recent publication of *Zielińska et al.* [36].
The aim of this proposal for the even-even Zn is to clarify the level scheme for ^{74}Zn and, thanks to the unique purity and intensity of the ISOLDE Cu beams, expand the level scheme for ^{76,78}Zn. Furthermore, for the lifetimes, we intend to corroborate the value for the 2_1^+ state, clarify results for the 4_1^+ state in ^{74}Zn and to measure for the first time the 4_1^+ state half-life in ^{76,78}Zn, expected to be above 18 ps, within the fast-timing capabilities of the setup.
Additionally, we ask to run a short test on the production of ^{80}Cu, that decays to ^{80}Zn, with N = 50, just two protons above the "doubly-magic" ^{78}Ni. Recently, the tentative

Isotope	$T_{1/2}$	Yield [ions/μC]	β-γ_{LaBr}-γ_{LaBr} [Counts/shift]	β-γ_{LaBr}-γ_{Ge} [Counts/shift]	Shifts
^{74}Cu	1.594 s	$6.0{\cdot}10^5$	$2.0{\cdot}10^2$	$1.0{\cdot}10^3$	1
^{75}Cu	1.224 s	$1.5{\cdot}10^5$	$1.0{\cdot}10^3$	$5.1{\cdot}10^3$	1
^{76}Cu	0.641 s	$2.0{\cdot}10^4$	$1.6{\cdot}10^2$	$7.8{\cdot}10^2$	2
^{77}Cu	469 ms	$2.0{\cdot}10^3$	15	75	3
^{78}Cu	342 ms	$2.0{\cdot}10^2$	4.6	23	7
^{79}Cu	188 ms	$2.0{\cdot}10^1$	7.1	35	9
^{80}Cu	170 ms	~ 1	?	?	1 *

Table 1: Summary of the Yields expected, counts expected for the most relevant transitions applying β-γ_{LaBr}-γ_{LaBr} and β-γ_{LaBr}-γ_{Ge} coincidences, and the shifts estimated for each Cu isotope. The $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions energies and branching ratios were used for the even isotope calculations. In the odd case, the coincidence between the first state and the strongest feeding transition was used. (*) This 1 shift will be dedicated to investigate the production and purity of the ^{80}Cu beam.

(4_1^+) state of ^{80}Zn has been observed for the first time by *Shiga et al.* [27]. We are aware of the challenge of producing this kind of exotic beam and expect a significant contaminant presence, but a yield of ~1 pps for 1 shift should be enough to observe the $2_1^+ \rightarrow 0_1^+$ and confirm the transitions from Ref. [34, 27]. Should this short test be successful, a full proposal aimed specifically at measuring the ^{80}Cu decay will be submitted.

3 Experimental method

For many years the ISOLDE facility has a unique capability to produce intense and high-purity beams. After the recently target developments and the ISOLDE Resonance Ionization Laser Ion Source (RILIS) improvements, several successful experiments in the Cu neutron rich region were carried out with relative high intensity beams [37, 38]. It will allow us to perform this experiment with high perspectives.
The lighter radioactive beams will be produced in proton-induced fission reactions using a UC_X target, 2.0 μA proton intensity will be desirable. For the most exotic Cu beams the neutron converter is essential in order to suppress the neutron-deficient contaminants, like Rb. Unfortunately, the isobaric contamination in the neutron-rich region, Ga in this case, is impossible to eliminate. However, the largest level of contamination that we expect is two orders of magnitude higher than the Cu beam intensity (*T. Stora* private communication). This contamination will be reduced adapting the beam-gate time and tape cycles depending of the half-lives of the parent and the daughter. The ionization of the Cu isotopes will be produced by the ISOLDE RILIS. For standard operation the ionization scheme with wavelengths 327 nm + 288 nm will be used to enhance efficiency, see Ref. [39].
The proposed β-decay experiment will use the IDS setup consisting of the tape station equipped with a fast plastic scintillator close to the implantation point having almost 25% efficiency for β detection, coupled to a combination of four HPGe clover-type

detectors and two $LaBr_3$ (Ce) detectors to register β-delayed γ-rays for the fast-timing measurement. The analog-electronics required for fast-timing experiments will be supplied by UCM-Madrid. The expected total photopeak efficiency of the Clover detectors will be 5% at 1.0 MeV and 1% at 0.8 MeV for the $LaBr_3$ (Ce) detectors. The present intensity of the Cu beams will allow to make γ-γ coincidence studies to define the correct transition sequences and be able to discriminate transitions populated by the possible contaminants and β-delay neutron emission in the most exotic cases. The use of fast $LaBr_3$ (Ce) detectors will give us access to lifetime information in the tens of picoseconds range on the states in the daughter nuclei, therefore we will also be able to get information on the reduced transition probabilities. The yields expected, number of counts per shifts and the number of shifts required for each Cu isotope is shown in the Table 1.

Summary of requested shifts: We request 24 shifts (8 days) of beam-time and 2 shifts (1 shift of ^{138}Cs, 1 shift of ^{88}Rb and 0.1 shift of ^{24}Na) for fast-timing calibrations. This does not include the time needed to set up the beam, which we estimate to be 2 shifts.

References

[1] A. Huck, et al. *Phys. Rev. C*, 31:2226–2237 (1985).

[2] D. Steppenbeck, et al.

[3] R. F. Garcia-Ruiz, et al. *Nat Phys*, advance online publication (2016).

[4] M. Chartier, et al. *Nucl. Phys. A*, 701(14):433 – 436, 2002. 5th International Conference on Radioactive Nuclear Beams.

[5] P. T. Hosmer, et al. *Phys. Rev. Lett.*, 94:112501 (2005).

[6] R. Broda, et al. *Phys. Rev. Lett.*, 74:868–871 (1995).

[7] J. Hakala, et al. *Phys. Rev. Lett.*, 101:052502 (2008).

[8] Z. Y. Xu, et al. *Phys. Rev. Lett.*, 113:032505 (2014).

[9] K. Sieja and F. Nowacki. *Phys. Rev. C*, 81:061303 (2010).

[10] Y. Tsunoda, et al. *Phys. Rev. C*, 89:031301R (2014).

[11] A. Gottardo, et al. *Phys. Rev. Lett.*, 116:182501 (2016).

[12] X. F. Yang, et al. *Phys. Rev. Lett.*, 116:182502 (2016).

[13] T. Otsuka, et al. *Phys. Rev. Lett.*, 95:232502 (2005).

[14] K.T. Flanagan, et al. *Phys. Rev. Lett.*, 103:142501 (2009).

[15] K. Heyde and J. L. Wood. *Rev. Mod. Phys.*, 83:1467–1521 (2011).

[16] R. A. Surman, et al. *Neutron Capture rates and r-process nucleosynthesis*, In *Capture Gamma-Ray Spectroscopy and Related Topics*, chapter 41, pages 304–313. World Scientific, 2013.

[17] R. Orlandi, et al. *Phys. Lett. B*, 740:298–302 (2015).

[18] M. Niikura, et al. *Phys. Rev. C*, 85:054321 (2012).

[19] C. Louchart, et al. *Phys. Rev. C*, 87:054302 (2013).

[20] D. Mücher, et al. *Phys. Rev. C*, 79:054310 (2009).

[21] S Hellgartner. *Probing Nuclear Shell Structure beyond the N = 40 Subshell using Multiple Coulomb Excitation and Transfer Experiments.* PhD thesis, Physik - Department, Technischen Universität München, 2015.

[22] M. Zielińska. *Private comunication.*

[23] I. Celiković, et al. *Act. Phys. Pol. B*, 44:375–380 (2013).

[24] H. Mach, R.L. Gill, and M. Moszyński. *Nucl. Inst. and Meth. in Phys. A*, 280(1):49 – 72, 1989.

[25] M. Moszyński and H. Mach. *Nucl. Inst. and Meth. in Phys. A*, 277(2-3):407 – 417, 1989.

[26] National Nuclear Data Center (NNDC). *http://www.nndc.bnl.gov.*

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

[28] M. Honma, et al. *Phys. Rev. C*, 80:064323 (2009).

[29] J. P. Delaroche, et al. *Phys. Rev. C*, 81:014303 (2010).

[30] S. M. Lenzi, et al. *Phys. Rev. C*, 82:054301 (2010).

[31] T. Otsuka. *Private comunication.*

[32] T. Faul. *Etude de la structure des Noyaux Riches en Neutrons autour du Noyau Doublement Magique ^{78}Ni.* PhD thesis, Université Louis Pasteur de Strasbourg, 2011.

[33] P.R. John. *Study of shape evolution in the neutron-rich osmium isotopes with the advance gamma-traking array AGATA.* PhD thesis, Dipartamento di Fisica e Astronomia "Galileo Galilei", Università degli Studi di Padova, 2015.

[34] J. Van de Walle, et al. *Phys. Rev. C*, 79:014309 (2009).

[35] E. Rapisarda et al. *INTC proposal P-353*, 2013.

[36] M. Zielińska, et al. *Eur. Phys. J. A*, 52(4):1–14, 2016.

[37] G. Neyens et al. *INTC proposal P-316*, 2011.

[38] V. Manea et al. *INTC proposal P-321*, 2012.

[39] The ISOLDE RILIS. *http://rilis.web.cern.ch/*.

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
IDS	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[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			
Temperature	[temperature] [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)			
Beam intensity			
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			
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]