EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Shell structure of odd neutron-rich $^{71-75}$Cu isotopes via one proton transfer reactions.

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Abstract: We propose to study neutron rich Cu isotopes with N=42, 44, 46 in the region of doubly magic neutron-rich ^{78}Ni nuclide via $^{72-76}$Zn(d,^{3}He)$^{71-75}$Cu transfer reactions. In particular, we aim at mapping the evolution of the proton $1f_{7/2}$-$1f_{5/2}$ spin-orbit partners along the Cu isotopic chain, approaching neutron-rich ^{75}Cu. The cross sections for excited states, the spin of the states and the spectroscopic factors will be measured for the low-lying states populated by the transfer reactions. The SpecMAT Active Target will be used as an experimental setup at HIE-ISOLDE. SpecMAT is composed of an active target – time projection chamber and an array of scintillation detectors that will be installed inside the ISOLDE Solenoidal Spectrometer (ISS).

Requested shifts: 51 shifts of beam time: 13 shifts of ^{72}Zn, 13 shifts of ^{74}Zn and 25 shifts of ^{76}Zn (splited into 2 runs: 1st run 13 shifts of ^{72}Zn and 2nd run 38 shifts of ^{74,76}Zn)
Beamline: 2nd beamline

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Introduction

A key challenge presented by present-day nuclear spectroscopy is mapping the evolution of nuclear orbitals. Systematic changes in the distances between nuclear orbitals can shed light on terms of the nucleon-nucleon interactions such as the tensor component. The magnitude of these changes could be used for estimation of the tensor force strength and provide experimental evidence of the existence of 'unconventional' magic numbers in certain regions of the nuclear chart. One of the regions where research is focused on the orbitals evolution is the region of doubly magic neutron-rich ^{78}Ni. Despite the experimental challenges required to produce suitable beams for experiments, this region became a focus of extensive experimental [1 - 4] and theoretical [5 - 9] research.

Copper isotopes have one proton above the $1f_{7/2}$ shell closure which makes them ideal candidates for systematic studies of the shell migration in this region. One of the first pieces of experimental evidence of the the energy of the $5/2^-$ state (proton in $1f_{5/2}$) lowering along the Cu isotopic chain with increasing number of neutrons was shown in Ref. [10]. Few years later the first observation of nuclear states inversion was published in Ref. [1], where measurements were obtained by a combination of in-source and collinear laser spectroscopy. In this work, Flanagan and collaborators also observed the migration of the $5/2^-$ state in ^{69}Cu – ^{75}Cu and discovered inversion between the $3/2^-$ and the $5/2^-$ states in ^{75}Cu, where the ground-state was shown to be $5/2^-$. This discovery was later confirmed with in-source laser spectroscopy technique [11]. The experimental evidence of the migration was theoretically described by the action of the tensor component of the monopole interaction [7, 8]. As reported in Ref. [7] for Ni isotopes the tensor forces has an attractive effect on $\nu 1g_{9/2}$ and $\pi 1f_{5/2}$ orbits with antiparallel spin and acts repulsive between $\nu 1g_{9/2}$ and $\pi 1f_{7/2}$ orbits with parallel spin. Based on this interpretation, the best way to quantify the monopole migration is to measure spin-orbit splitting between $\pi 1f_{5/2}$ and $\pi 1f_{7/2}$ because tensor force has opposite effect on $f_{5/2}$ and $f_{7/2}$ orbits. The present proposal aims at further investigation of the $f_{5/2}$-$f_{7/2}$ shell evolution by studying the variation of the energy gap between the proton single-particle orbitals with rising number of neutrons filling the $\nu 1g^{9/2}$, namely scanning the Cu isotopic chain.

Transfer reactions represent a powerful technique which facilitates single-particle states population around shell closures [13, 14]. When dealing with radioactive beams of very exotic ions one has to face challenges due to the low beam intensity, negative reaction Q-values and inverse kinematics. To overcome these limitations, an innovative method based on an active target - time projection chamber (TPC) placed in a high magnetic field will be employed.

Physics motivations

Otsuka and collaborators predicted the narrowing of the Z=28 shell gap for neutron-rich Ni isotopes [7] filling the $\nu 1g_{9/2}$ orbit which casts some doubt on the existence of the 28 number magicity approaching ^{78}Ni. In a later work [8], the same authors developed an interaction containing both tensor and central forces. This approach allowed to obtain more accurate results, where single particle energies for Ni do not show dramatic narrowing of the Z=28 gap as previously obtained calculations.

Large-scale shell model calculations provided by Sieja and Nowacki [5] have been performed using ^{48}Ca core. The group has calculated the systematics of odd $^{69-79}$Cu accurately matching recent experimental results. This breakthrough result was obtained due to an enlarged valence space for protons using this new core instead of the usual ^{56}Ni core. In Fig. 1 calculated systematics for Cu isotopes are shown, where the narrowing of the Z=28 gap also was confirmed.

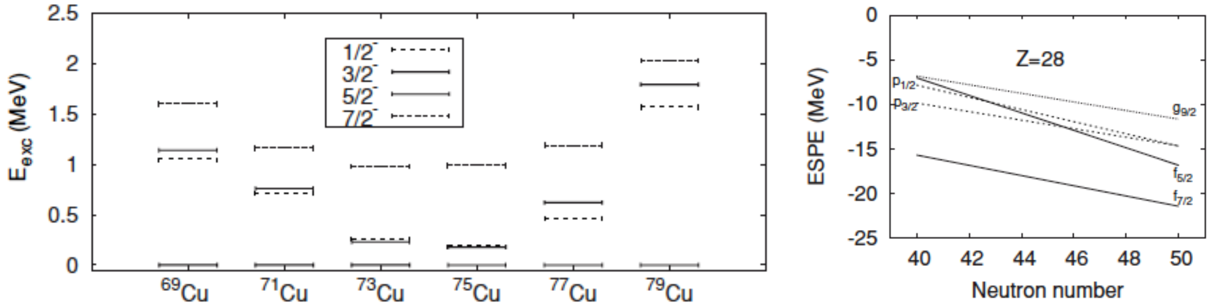

Fig. 1 Systematics of Cu isotopes predicted by the calculations (a). Calculated effective single particle energies (ESPE) as a function of neutron number for Ni isotopes (b). Taken from [5].

Calculations of Sieja and Nowacki agree quite well with the calculations of Otsuka. Still, the picture needs to be tested against experimental data.

The first experiment with (d,^{3}He) transfer reaction on stable even $^{64\text{-}70}$Zn isotopes was performed in [15]. In this work the first level scheme for ^{69}Cu was proposed and spectroscopic factors for low lying states of up to 7/2^{-} in odd $^{63\text{–}69}$Cu isotopes were measured. In 2013 this reaction was studied in Ref. [16 - 18]. In these works, the research group observed low lying states in ^{69}Cu isotope of up to 4 MeV (Fig. 2a), a 5/2^{-} state was measured at 1.23 MeV and the centroid of 7/2^{-} states at 2.45 MeV. The osition of the 5/2^{-} state is in a good agreement with the calculated value, however the 7/2^{-} centroid deviate from the calculations almost by 2 MeV. This discrepancy was described by the quite significant difference between the predicted and measured total strength of the states. Further simulation based on the experimental data showed that the position of the centroid is most probably located at 3.81 MeV.

Proton knockout reaction on ^{72}Zn isotope to study ^{71}Cu was performed at GANIL [17]. In this experiment, a solid (CD_2) deuteron target was exposed to a ^{72}Zn beam. ^{72}Zn was accelerated to 38MeV/u, light projectiles emitted from the reaction were detected by the MUST2 telescopes. Unlike the beta-decay observations published in Ref. [19] the 7/2^{-} states at 981keV and 1190keV were not populated in this experiment. Thus it was concluded that these two states could be populated mainly through particle coupling to a 2^{+}(^{70}Ni) core but not through a proton removal from $\pi 1f_{7/2}$ orbital as it was suggested in Ref. [19] and [20] for the state at 981keV. In Ref. [21] was confirmed that 981keV state originate from $\pi 1f_{5/2}$ orbital coupling to a 2^{+}(^{70}Ni) core. The centroid of the 7/2^{-} proton-hole states was experimentally determined to be 3.76 MeV (Fig. 2b).

Odd copper isotopes in this region were studied with multinucleon transfer reactions [21]. Authors in this work focused on characterisation and life time measurements of low-lying 7/2^{-} states in $^{69\text{-}73}$Cu.

We propose to measure cross sections for population of low-lying excited states in the Cu isotopes by one-proton peakup reactions $^{72\text{-}76}$Zn(d,^{3}He)$^{71\text{-}75}$Cu. Spins of the populated states will be determined based from the angular distribution. Through the (d,^{3}He) transfer reaction on even Zn isotopes it will be possible to populate single-hole states by removing one proton from $\pi 1p_{3/2}$, $\pi 1p_{5/2}$ or $\pi 1f_{7/2}$ orbitals. Thereby, these states will contain direct information on the monopole migration and the size of the Z=28 closure in this region.

Experimental results and calculations shown by Morfouace for ^{69}Cu in Ref. [17] point on the importance of detection 7/2^{-} states located above 4 MeV. These states carry relatively high strength and thereby might have a significant contribution to the weighted centroid position (Fig. 2a, right). Also, as it was shown in Ref. [17] some of the low-lying states with 7/2^{-} spin-parity in ^{71}Cu are collective and do not contain information on the $f_{7/2}$ orbit position. This confirms the necessity of using one proton removal reactions where population of single particle states is possible.

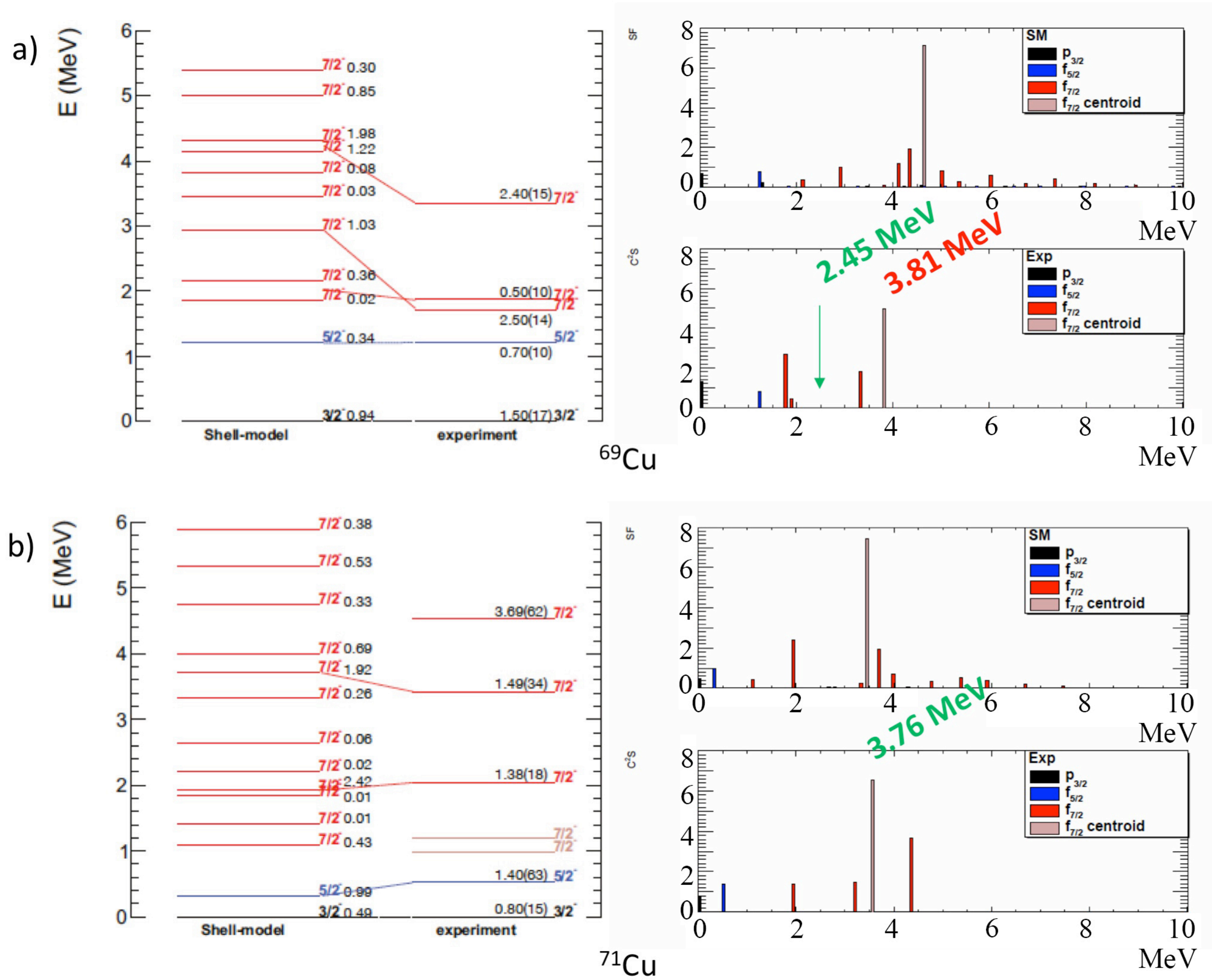

Fig. 2 Comparison of observed energy states in a) ^{69}Cu and b) ^{71}Cu via (d,^{3}He) transfer reaction. Experimentally centroids of the $f_{7/2}$ states were found to be 2.45 MeV (the arrow shows the real position of the centroid) and 3.76 MeV for 69Cu and 71Cu respectively (indicated in green). $f_{7/2}$ centroid at 3.81 MeV for ^{69}Cu was obtained after correction based on MC calculations (indicated in red). Taken from [17].

Since ^{71}Cu has been studied previously, we can use the ^{72}Zn(d,^{3}He) reaction to characterize the SpecMAT detector. On the other hand, reactions on ^{74}Zn and ^{76}Zn have never been studied and their measurement will provide new information on the structure of nuclei in this region. The reaction on ^{76}Zn plays a particularly important role as ^{75}Cu is a breaking point where the inversion between $p_{3/2}$ and $f_{5/2}$ ground states was observed. Excitation energy spectra for these isotopes will be extended with gamma-ray spectroscopy of the populated states. Spectroscopic factors will be deduced for the populated states.

Experimental method

Probing of the shell structure in $^{71\text{-}75}$Cu isotopes will be carried in inverse kinematics via (d,^{3}He) transfer reaction. One proton pick-up reaction was chosen because of several advantages. The pick-up reaction populations states with a single-hole character. ^{3}He has lower magnetic rigidity in comparison to a proton with the same kinetic energy and as a consequence smaller trajectory radius inside a magnetic field. Therefore, upper limit of detecting energies could be extended.

Experimental setup

The SpecMAT detector consists of a time projection chamber (TPC) surrounded by a gamma detection array (Fig. 3). The inner detector's volume will be filled with D_2 gas, which serve as a target and as a sensitive medium. When interacting with the gas, reaction products leave tracks of ionised electrons. These electrons are collected on a charge sensitive pixelated pad plane [22]. Projection of a particle track on the pad plane and a charge collection time are the core data to the particle identification procedure. SpecMAT detector is going to be placed in a high magnetic field of up to 3T to reconstruct the energy of the recoiled particle based on the curvature of the particle track. The array of scintillation detectors will be used for gamma spectroscopy of directly populated low-lying levels in the transfer reactions.

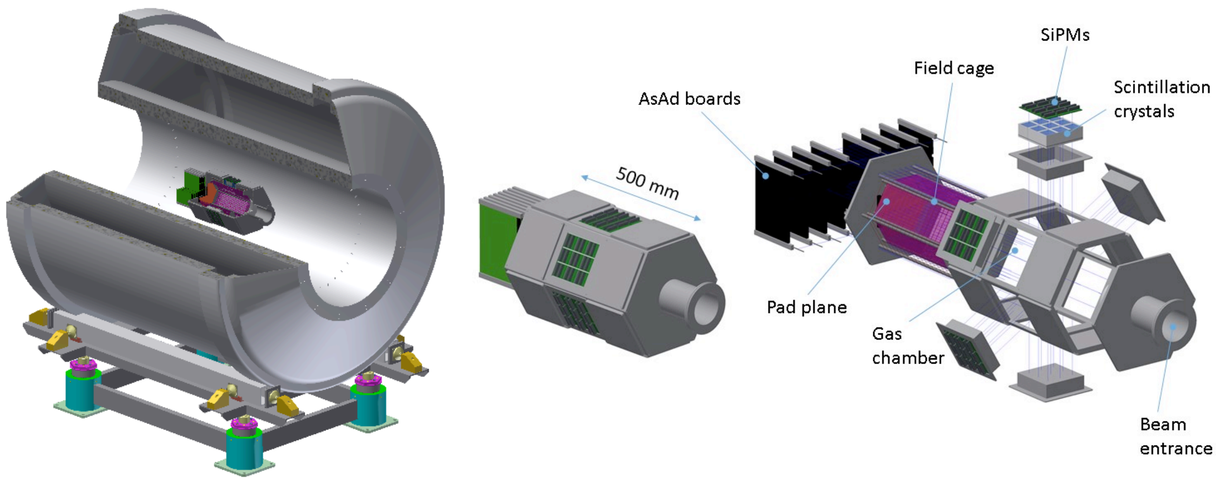

Fig. 3. Design of the SpecMAT Active Target -Time Projection Chamber. SpecMAT placed in the ISS magnet left, exploded view of the SpecMAT right.

SpecMAT will have about ten thousand output channels in combination with variety of ancillary detectors. To overcome the challenge of channel readout, General Electronics for TPC (GET) [23, 24] will be coupled to SpecMAT.

As it was shown for ACTAR TPC in [25] and MAYA detector in [26], detection efficiency of the reaction products in TPC might be as high as 90-100% at relatively low count rates. Similar efficiency we expect to achieve with the TPC of the SpecMAT detector. However, efficiency of SpecMAT is mainly limited by the efficiency of the scintillation array, which was simulated in GEANT4. Absolute efficiency of 7% was obtained for 1MeV gamma-ray detected with an array of 54 $LaBr_3$:Ce crystals arranged in a hexagonal shape. Each crystal in the simulation was a cube with 1.5”x1.5”x1.5” sides.

Beam-time request

The radioactive ^{72}Zn beam will be used for detector characterisation. The main limitations of the detection rate are coming from the electron drift time in the gas chamber, thereby beam intensity should not be higher than $1{\cdot}10^6$ pps in the SpecMAT detector. We expect to have the ^{72}Zn beam from UC_X target produced by RILIS ion source [27]. Supposing that proton beam current is 1.5μA and the beam transmission efficiency to the Experimental Station 2 (XT02) is the same as to Miniball, 5%, we can estimate that the beam yield should be not more than $7{\cdot}10^7$ ions/μC (Table 3).

We made the assumption that cross sections for population of low-lying states in $^{71\text{-}75}$Cu via (d,^{3}He) reaction are close to the already measured cross sections in the ^{70}Zn(d,^{3}He)^{69}Cu reaction, values of which were extracted from Ref. [17] and are shown in Table 1. It is clear that the measurement time is determined by the two $7/2^-$ states at 1.87 and 3.94 MeV with the smallest total cross section of 0.03 mb. Since the gas chamber of the detector could be filled at the pressure of 1 atm and the target length is 15 cm, thickness of the target will be 2.5 mg/cm^2. Taking into account the detector efficiency described above we expect to have gamma+^{3}He detection rate of 114 events/shift or 341 events/day (Table 2). To collect enough statistics, we would like to detect at least 1000 events leading to 9 shifts of the beam time. Also we are considering the fact that the beam purity of the all requested beams might reach 95% with 5% of Ga contamination. For identification events coming from the reactions on ^{72}Ga we will use the laser ON/OFF technique where the beam produced with laser OFF should take not less than 1/8 of the total experimental time based on the previous experiments with MINIBALL. In the case of ^{72}Zn beam 2 shift with laser OFF will be necessary. Adding 2 shifts for beam tuning we are requesting a total of 13 shifts of ^{72}Zn beam (Table 3).

For ^{74}Zn and ^{76}Zn the yields were provided by T. Stora Ref. [28] (Table 2 and 3).

Table 1 Total cross sections for population low lying states in ^{69}Cu via (d,^{3}He) reaction based on the experiment of Morfouace et. al. [17]

Isotope	State	Energy, MeV	Estimated total cross-section, mb
^{69}Cu	g.s. $3/2^-$	0	0.82
	$5/2^-$	1.23	0.04
	$7/2^-$	1.71	0.19
	$7/2^-$	1.87	0.03
	$7/2^-$	3.35	0.11
	$7/2^-$	3.7	0.05
	$7/2^-$	3.94	0.03

Table 2 Expected gamma detection rates for (d,^{3}He) transfer reaction on Zn. For each Cu isotope only the excited state with the smallest population probability is shown.

Beam	Estimated beam intensity at SpecMAT, pps	Produced isotope	Excited state	Estimated gamma+^{3}He detection rate, events/shift
^{72}Zn	$5 \cdot 10^6$	^{71}Cu	$7/2^-$	113.6
^{74}Zn	$4.92 \cdot 10^6$	^{73}Cu	$7/2^-$	111.7
^{76}Zn	$1.14 \cdot 10^6$	^{75}Cu	$7/2^-$	25.9

Summary of requested shifts:

Table 3 Requested beams

Beam	**Energy, MeV/u**	**Yield, ions/μC**	**Target**	**Ion source**	**Requested shifts**			
					Beam tuning	Laser ON	Laser OFF	**Total**
^{72}**Zn**	**10**	**7·10^{7}**	UC_X	RILIS	2	9	2	**13**
^{74}**Zn**	**10**	**6.9·10^{7}**	UC_X	RILIS	2	9	2	**13**
^{76}**Zn**	**10**	**1.7·10^{7}**	UC_X	RILIS	2	20	3	**25**

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Appendix 1

Status of the SpecMAT detector

The SpecMAT active target detector is being built in Leuven within the SpecMAT project, financed by an ERC Consolidator Grant (PI R. Raabe, 2014-2019).

The detector is designed for the detection of direct transfer reactions in inverse kinematics. The principle of an active target is to use a gas as target and at the same time as detection medium. SpecMAT aims at combining the advantages of an active target (large target thickness and thus high luminosity without loss of energy resolution) with the detection of γ-rays in an efficient array of scintillators. The charged particles emitted in the reactions are identified through their energy loss in the gas and the radius of cyclotron motion, induced by a magnetic field. The tracks are reconstructed through their projection, realised by the detection of ionisation electrons which are guided by an electric field (collinear to the magnetic field) on the pad plane located on one of the end caps of the gas volume.

The resulting design is as shown in Fig. 3 of the proposal: the gas chamber is surrounded by the array of scintillators in a compact geometry, and the ensemble is placed within the solenoid. The latter is the ISS already foreseen to be placed at ISOLDE.

There is a close collaboration with the UK groups for the integration of both setups (silicon detectors for the ISS and SpecMAT) in the solenoid. A rail system will allow to swap the two detection setups with minimal effort. Notice that for the SpecMAT configuration it will not be necessary to have vacuum inside the solenoid.

The Leuven group participates in the costs for the maintenance of the solenoid.

In Leuven, we have finalised the tests on prototype LaBr3 scintillators and electronics in strong magnetic fields. We could validate the preferred configuration which uses silicon photomultipliers for the read-out, coupled to digital electronics, and notice only a modest and acceptable decrease of the resolution with respect to the nominal values.

The tender for the scintillators was launched, the delivery of the detectors will take place (in batches) during 2017.

Concerning the active target itself, SpecMAT uses the results and expertise obtained within the ACTAR TPC collaboration (R. Raabe is co-spokesperson). The design of the pad plane and the electro-mechanic solutions have been validated in the tests of the ACTAR TPC Demonstrator.

The addition of a magnetic field will not add complications, as shown by the AT-TPC active target at MSU which shares a similar design (without scintillators) and is immersed in a 3T magnetic field.

We are now realising a prototype about half the size of the final detector, with a reduced number of electronic channels, and plan to test it with the first delivered scintillators using sources and stable beams in the summer of 2017.

The digital electronics (GET) for the tests has been purchased. For the final detector, we will use the GET modules of the ACTAR TPC collaboration.

We plan to have the mechanics of the final detector assembled for mounting in the ISS solenoid during the 2017-2018 shut-down period. Adjustments will still be possible before the runs in the summer/fall of 2018.

Appendix 2

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
	☐ Existing	☐ To be used without any modification
SpecMAT active target time projection chamber	☐ 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
ISOLDE Solenoidal Spectrometer (ISS)	☐ 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 [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards	*SpecMAT*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	1 [Bar], 22 [l]		
Vacuum			
Temperature	293 [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	Field cage: Up to 10 [kV], Pad plane: Up to 1 [kV]		
Static electricity			
Magnetic field	3 [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	Deuterium (D_2) gas		
Beam particle type (e, p, ions, etc)	ions		
Beam intensity	Up to $5{\cdot}10^6$ pps		
Beam energy	10MeV/u		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		

• Open source	☒		
• Sealed source	☒ [ISO standard]		
• Isotope	Standard alpha and gamma calibration sources		
• 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 (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	D_2, 22 [l]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	D_2, 22 [l]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
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]		

0.1 Hazard identification

3.2 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)*

… kW