EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

(Following HIE-ISOLDE Letters of Intent I-119, I-191, I-194, I-195)

The SpecMAT active target

October 17, 2018

R. Raabe[1], M. Babo[2], S. Ceruti[3,4], H. De Witte[1], T. Marchi[5], A. Mentana[1], O. Poleshchuk[1],
A. A. Raj[1], J. Refsgaard[1], M. Renaud[1], J. Yang[1],
the ACTAR TPC Collaboration,
and the ISS Collaboration

[1]*KU Leuven, Instituut voor Kern- en Stralingsfysica, 3001 Leuven, Belgium*
[2]*Institut de Physique Nuclaire, CNRS-IN2P3, 91406 Orsay, France*
[3]*Dipartimento di Fisica dell'Università degli Studi di Milano, I-20133 Milano, Italy*
[4]*INFN, Sezione di Milano, I-20133 Milano, Italy*
[5]*INFN, Laboratori Nazionali di Legnaro 35020, Italy*

Spokesperson: [Riccardo Raabe] [riccardo.raabe@kuleuven.be]
Contact person: [Liam Gaffney] [liam.gaffney@cern.ch]

CERN-INTC-2018-031 / INTC-M-020
18/10/2018

Abstract: This Memorandum describes the physics case for the SpecMAT active target at ISOLDE and its current status. SpecMAT aims at measuring direct reactions for the study of single-particle and collective states in nuclei far from stability, using the post-accelerated beams of HIE-ISOLDE. The detection is based upon the active-target concept, that allows tracking the charged particles inside a gas volume, while the gas particles are also the target of the reaction to be studied. In SpecMAT, this is coupled to γ-ray detectors to resolve closely-spaced states in the product nuclei. The target will be placed inside the magnet of the ISS spectrometer, exploiting the magnetic field to identify the emitted particles through the properties of their curved tracks in the gas.

Requested shifts: —
Installation: SpecMAT inside the ISS magnet

1 Introduction

Active targets are gaseous detectors based on the concept of the time-projection chamber (TPC): charged particles traversing the detection volume produce an ionisation track, which is reconstructed by collecting the electrons in an electric field onto a position-sensitive cathode. In addition, the detection medium — the gas — is also the target of a nuclear reaction of interest. Thanks to the identification of the reaction vertex, the instrument potentially provides a high luminosity without the loss in resolution that appears when using a conventional thick target (a foil) in inverse kinematics. Other advantages are its versatility and potential in particle identification.

After the success of the first active targets for nuclear structure studies (such as IKAR [1] and Maya [2]), a second generation has been designed and realised with the main aims of improving the dynamic range, the spatial and energy resolution and the reconstruction efficiency. The efforts are coordinated in Europe by the ACTAR TPC Collaboration. A first Letter of Intent I-119 [3] was presented in 2010 and endorsed by the INTC, about the use of active targets for the measurement of direct and resonant reactions at HIE-ISOLDE.

ACTAR TPC, currently installed at GANIL (Caen, France), is the first of the new devices to be completed. It is a cubic active target, with the drift field perpendicular to the beam direction. The collection plane uses the Micromegas amplification technology [4]; it has 128 × 128 pads, each $2 \times 2\,\mathrm{mm}^2$, for a total of 16384 channels, read out by the custom-designed GET electronics [5]. Auxiliary silicon detectors can be placed around the gas detection volume to identify and measure the energy of particles not stopped in the gas. The commissioning measurements with a ^{58}Ni beam has shown an energy resolution for elastic scattering on protons of about 100 keV in the center of mass [6]. At ISOLDE, two accepted experiments [7, 8] plan to use ACTAR TPC on the third beam line of HIE-ISOLDE.

The SpecMAT active target (ERC CoG Grant 617156), to be installed at ISOLDE, shares some characteristics with ACTAR TPC, such as the Micromegas amplification technology and the GET readout electronics. It has, however, a different design, adding γ-ray scintillation detectors ($CeBr_3$ crystals) in order to resolve closely-spaced populated states in reactions with medium- and heavy-mass nuclei. The properties of charged particles emitted in the reactions are measured through the characteristics of their tracks, which are bent in a strong magnetic field: SpecMAT will be placed inside the magnet of the ISOLDE solenoidal spectrometer (ISS). The electric drift field is parallel to the beam direction, and the ionisation electrons are collected onto a pad plane perpendicular to the beam.

2 The Physics Case of SpecMAT

The SpecMAT project initially focused on two regions of the chart of nuclei, where transfer reactions are planned: the neutron-rich Ni region and the n-deficient Pb region. In addition, the possibility of studying the pigmy dipole resonance has also been explored. In 2017, we have entered LoIs to the INTC to explore the possibility of using long-living or stable isotopes in the period before the re-start of operation of CERN accelerators in 2021.

2.1 Transfer Reactions

The neutron-rich Ni region is a key one for the study of the evolution of nuclear shells far from stability, and it has been long investigated by the research groups in Leuven with a number of experimental techniques. The most advanced shell-model calculations are performed on these isotopes, allowing to connect the observed features with the properties of the underlying nucleon-

nucleon interaction.

For example, the tensor interaction between protons and the neutrons filling the $g_{9/2}$ orbital between $N = 40$ and $N = 50$ leads to the lowering of the proton-$f_{5/2}$ orbital, which becomes the lowest in energy above $Z = 28$ as observed in the ground-state spin-parity of ^{75}Cu [9]. A direct measurement of the proton $f_{7/2}$–$f_{5/2}$ spin-orbit gap in Cu isotopes would put strong quantitative constraints on the calculations.

Similarly, the evolution of the single-particle energy of the neutron orbitals above $N = 50$ (mainly $2d_{5/2}$ and $3s_{1/2}$), when removing protons from ^{86}Kr down to ^{78}Ni, could be addressed by the characterisation of the excited states in ^{81}Zn.

Still in this region, the interplay between single-particle and collective degrees of freedom and the origin of shape coexistence can be investigated by characterising the low-lying 0^+ and 2^+ states in neutron-rich even Ni isotopes [10, 11]. These studies could be extended to the nuclei below Ni, where an "island of inversion" has ben predicted [12]. The same issue is of course central in the region of neutron-deficient Pb isotopes, where the best-known manifestations of shape coexistence are to be found. By measuring transfer-reaction cross sections, it will be possible to characterise the configurations of low-lying states in, for example, Hg isotopes. By adding or removing a neutron to/from the ground state of even-even isotopes, the information is obtained from the relative population of states in the odd-mass neighbour, where states with different configurations have different spins and do not mix. Alternatively, one can start from selected states in the odd isotopes, which can be produced at ISOLDE as isomerically-purified beams. With SpecMAT, the addition of γ-ray detection would help assigning excited states to the respective deformation band.

Our proposal P-495 [13] explored the possibility of measuring the $f_{7/2}$–$f_{5/2}$ spin-orbit splitting in Cu nuclei, through the proton-removal (d,^{3}He) reaction on Zn isotopes, reaching as far as ^{75}Cu. The INTC deemed the proposal premature, on the basis of SpecMAT not being ready and possible relevant data from a proton knock-out measurement at MSU. We then presented the LoI I-191 [14], about using the stable ^{70}Zn isotope to perform the same transfer reaction, possibly during the LS2 shutdown. A measurement in ^{69}Cu would give a reference for the value of the $f_{7/2}$–$f_{5/2}$ splitting, since the protons should experience no tensor force from the neutron-$g_{9/2}$ orbital.

The LoI I-195 [15], on the other hand, concerned the measurement of (p,d), (d,t) and (d,p) reactions in Hg isotopes, by using a beam of the long-living ^{194}Hg or the stable ^{196}Hg isotopes, to probe the evolution of neutron single-particle states.

2.2 Study of the Pigmy Dipole Resonance

The measurement of collective resonances using inelastic scattering in inverse kinematics is very challenging due to the low energy of the recoil particle in the events of interest at small centre-of-mass angles. Next to storage rings, where a proof-of-principle measurement on the stable ^{58}Ni was performed [16], active targets have proven very successful, with the identification of isoscalar modes in ^{56}Ni [17, 18] and ^{68}Ni [19, 20].

While most of the $E1$ strength is found in the giant dipole resonance (GDR), in nuclei with $N > Z$ some strength is observed at a lower energy, around the neutron separation energy. While the actual nature of that low-lying strength is still debated, it could be explained by a collective excited state, called Pygmy Dipole Resonance (PDR), representing the oscillation of excess neutrons against the $N = Z$ core. Besides nuclear structure, the PDR has implications in nuclear astrophysics, where its presence around the neutron separation threshold could affect the neutron capture rate in the r-process.

The PDR exhibits both an isoscalar (IS) and isovector (IV) nature, and its total strength can

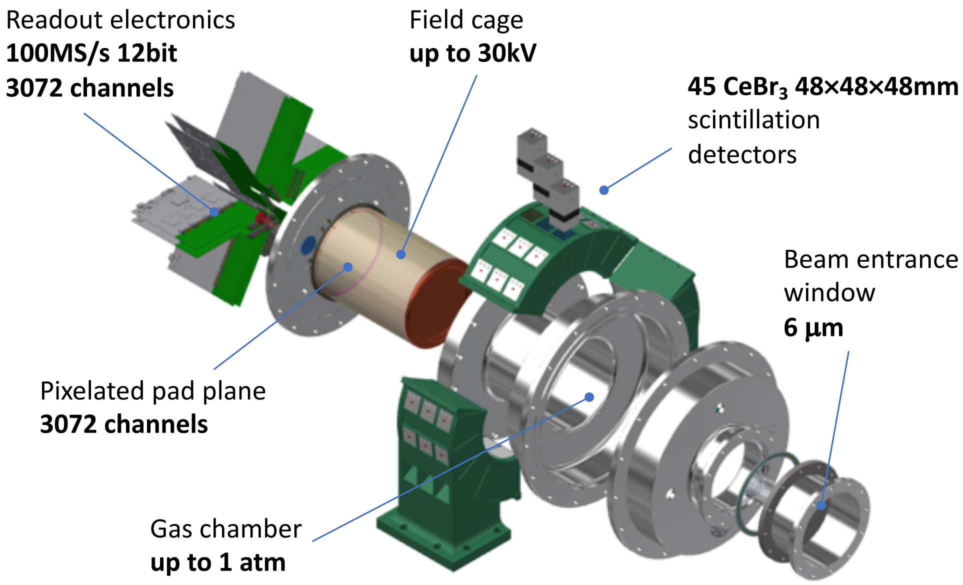

Figure 1: Exploded view of the SpecMAT detector with indication of the main components.

be obtained in (γ,γ') experiments. By using an hadronic probe, on the other hand, the isoscalar part can be selectively populated. Measurements in ^{140}Ce [21] have shown that the isoscalar character resides in the lowest part of the PDR, which would be associated with a neutron-skin oscillation [22].
SpecMAT would be particularly suited for the measurement of the PDR in neutron-rich nuclei, as it combines the detection of the low-energy light-hadron recoil and of the de-excitation γ rays. The LoI I-194 [23] was entered to the INTC in 2017, to perform such experiments on neutron-rich long-living or stable nuclei, for example ^{90}Sr, ^{194}Hg, ^{146,148,150}Gd.

3 Technical Aspects

3.1 The active target

The SpecMAT active target, as mentioned, is composed of a field cage, surrounded in close geometry by scintillation crystals. At the two ends of the cage there are the cathode and the Micromegas pad detector. An overview of the different parts is shown in Fig. 1.
The whole instrument will be placed inside the magnet of the ISS on the second beam line of HIE-ISOLDE, see Fig. 2. For this, the large flanges (end caps) of the ISS will be removed and the beam line will be directly connected to the SpecMAT chamber. An entrance window separates the vacuum of the beam line from the gas-filled volume of the active target. The detector can be operated at different pressures, from a few tens of mbar to 1 bar.
The beam traverses the gas volume and in particular the field cage, where the reactions of interest are recorded. The field cage is 30 cm long and 23 cm in diameter, and is designed (together with all the elements of the chamber) for a field of up to 1 kV/cm. Thanks to the field of the ISS magnet, the light charged particles emitted in the reactions are (partially) confined in the field cage, producing ionisation tracks characteristics of their mass, charge and energy. The electrons from the ionisation are collected on a pad plane which, in a first test configuration, has triangular pads of about 5-mm side for a total of 3072 pads. A final configuration will

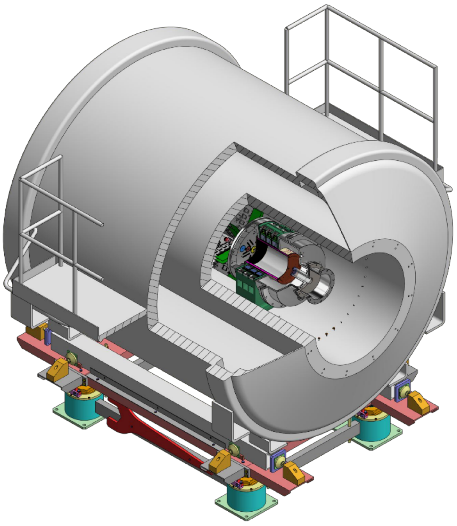

Figure 2: The SpecMAT detector placed inside the ISS magnet.

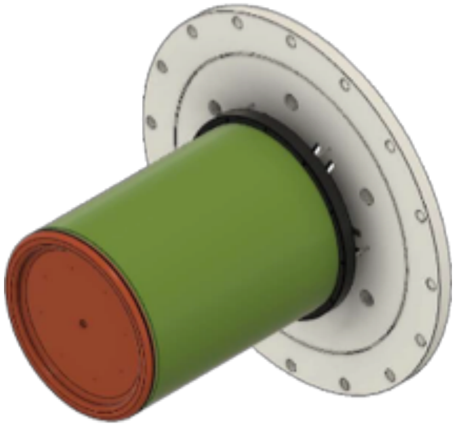

Figure 3: The field cage and pad plane unit, shown here as mounted on the back flange of SpecMAT.

increase the number of pads to more than 10000 by reducing their size to a 3-mm side. The pad plane and the cage are realised as one unit at CERN by the Micro-Pattern Technologies group (EP-DT-DD MPT), see Fig. 3. The pads are read out by the GET electronics [5]. The front-end ASAD modules, each capable of processing 256 channels, are mounted on the back flange of the SpecMAT chamber. They are connected through 8-m long cables (one per board) to Concentration Boards (CoBo), situated in racks outside the shield cage of the ISS magnet.

The array of $CeBr_3$ scintillator crystals closely surrounds the field cage. The cubic scintillators ($48\times48\times48\,\mathrm{mm}^3$, see Fig. 4 left) are placed in a lightweight structure (Fig. 4 centre), for a simulated photo-peak efficiency of about 8% at 1 MeV energy, on the whole length of the active volume. The nominal resolution of the detectors is 3.9% at 661 keV energy. On each crystal, light collection is performed by a $50\times50\,\mathrm{mm}^2$, 64-element array of silicon photomultipliers (SiPM). The GET electronics will also be employed for the readout of the scintillators. The tests performed in a high magnetic field of 3 T did not show any degradation of the energy resolution.

3.2 Installation

To place the SpecMAT chamber inside the ISS magnet, a platform and a rail system have been designed, see Fig. 5. For this operation the magnetic field of the ISS will be switched off. The screen, forming part of the ISS shield cage at the back of the magnet, will be temporarily removed; this is also necessary to remove the structure supporting the setup currently in the ISS (target and silicon array of the pure “solenoidal spectrometer” mode). Once the chamber is in the magnet, the external platform will be removed and the shielding plate will be put back in its place.

For the electronics and the operation of the gas system, the same racks which are currently occupied by the ISS electronics will be used, outside the shielding cage of the magnet. Cables and gas inlets will run along the existing cable trays.

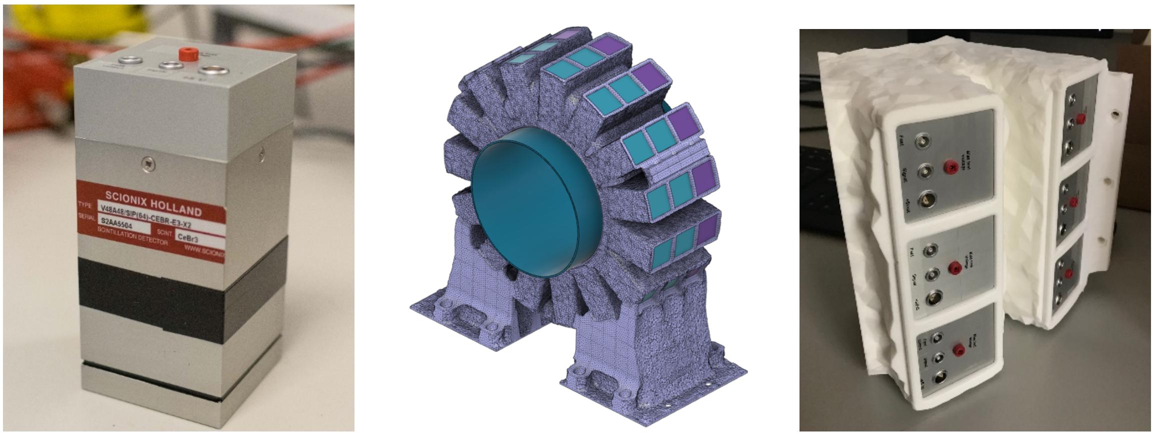

Figure 4: Left: one of the $CeBr_3$ scintillation crystals of the array. Centre: the lightweight array-holding structure. Right: prototypes of the structure.

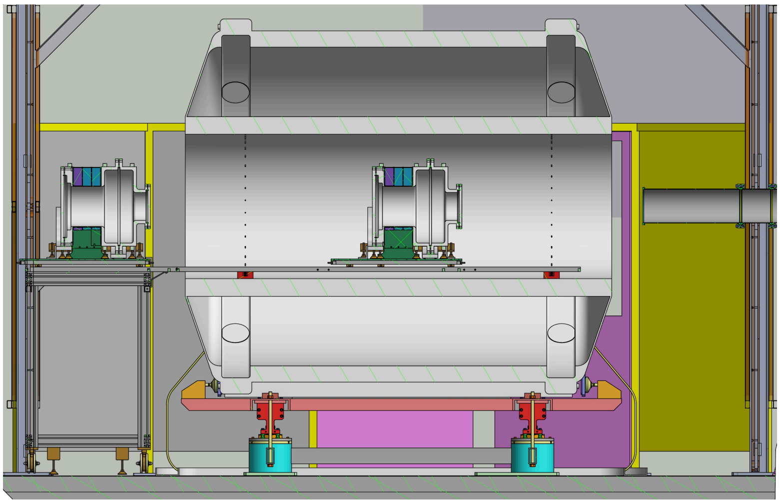

Figure 5: External platform and rails to slide the SpecMAT chamber inside the ISS magnet.

4 Status and Planning

At present, the detectors of the γ-ray array have been delivered and are being fully characterised at our home laboratory in Leuven. The supporting structure (Fig. 4) has also been very recently delivered.
The vacuum chamber (mechanical parts) have been procured, the delivery is scheduled before the end of this year. A similar time frame is foreseen for the field cage, which is being finalised at CERN. As well, the external platform and rail system are being manufactured at the mechanical workshop of the KU Leuven.
The GET electronics for the 3072 channels of the initial configuration is available in Leuven (2048 channels) and with the collaboration partner in Legnaro (2048 channels).

In the present planning, a first assembly will be made in Leuven in the beginning of 2019. This will be followed by a characterisation of the instrument, and specifically:

- characterisation of the γ-ray array using calibration sources: resolution, efficiency, thresholds;

- leak tests of the detector chamber;
- commissioning of the gas control system for pure gases and mixtures;
- tests of the electric field cage: sparking limits with different gas pressures and compositions;
- characterisation of particle tracks in the active gas volume using α-particle calibration sources: linear and angular resolutions, resolution in reconstructed energy deposition.

These measurements will also provide all the specifications needed for access clearance at ISOLDE. Once the tests are completed, the detector will be moved to CERN for the installation in the ISS magnet. This step will be coordinated, within in the ISS collaboration, with the installation (latest in the summer of 2019) of the new silicon detector array of the ISS in the solenoidal spectrometer mode.

Our aim is to have SpecMAT completely tested for operation in the magnetic field by the end of 2019/beginning 2020. If stable-ion beam time is available prior to the start of CERN operations in 2021, we would like to perform the transfer-reaction measurements mentioned in the LoIs I-191, I-194 and I-195.

References

[1] G. D. Alkhazov, *et al.*, Phys. Rev. Lett. **78**, 2313 (1997).

[2] C. E. Demonchy, *et al.*, Nucl. Instrum. Methods Phys. Res. A **573**, 145 (2007).

[3] R. Raabe (spokesperson), *et al.*, "Letter of Intent to the INTC I-119: Direct and resonant reactions using an Active Target" (2010).

[4] Y. Giomataris, P. Rebourgeard, J. Robert, and G. Charpak, Nucl. Instrum. Methods Phys. Res. A **376**, 29 (1996).

[5] E. C. Pollacco, *et al.*, Nucl. Instrum. Methods Phys. Res. A **887**, 81 (2018).

[6] B. Mauss, *Réactions élastiques et inélastiques résonantes pour la caractérisation expérimentale de la cible active ACTAR TPC*, Ph.D. thesis, Université de Caen Normandie (2018).

[7] M. Veselsky (spokesperson), *et al.*, "Proposal to the INTC P-356: (d,p)-transfer induced fission of heavy radioactive beams" (2012).

[8] B. Fernández-Domínguez (spokesperson), *et al.*, "Proposal to the INTC P-366: Study of the unbound proton-rich nucleus ^{21}Al with resonance elastic and inelastic scattering using an active target" (2012).

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

[10] Y. Tsunoda, T. Otsuka, N. Shimizu, M. Honma, and Y. Utsuno, Phys. Rev. C **89**, 031301 (2014).

[11] S. Leoni, *et al.*, Phys. Rev. Lett. **118**, 162502 (2017).

[12] S. M. Lenzi, F. Nowacki, A. Poves, and K. Sieja, Phys. Rev. C **82**, 054301 (2010).

[13] O. Poleshchuk (spokesperson), *et al.*, "Proposal to the INTC P-495: Shell structure of odd neutron-rich $^{71-75}$Cu isotopes via one proton transfer reactions " (2017).

[14] O. Poleshchuk (spokesperson), *et al.*, "Letter of Intent to the INTC I-191: Single-particle proton states in ^{69}Cu" (2017).

[15] M. Babo (spokesperson), *et al.*, "Letter of Intent to the INTC I-195: Investigating single-particle configurations in deformed Hg and Cd isotopes" (2017).

[16] J. C. Zamora, *et al.*, Phys. Lett. B **763**, 16 (2016).

[17] C. Monrozeau, *et al.*, Phys. Rev. Lett. **100**, 042501 (2008).

[18] S. Bagchi, *et al.*, Phys. Lett. B **751**, 371 (2015).

[19] M. Vandebrouck, *et al.*, Phys. Rev. Lett. **113**, 032504 (2014).

[20] M. Vandebrouck, *et al.*, Phys. Rev. C **92**, 024316 (2015).

[21] J. Endres, *et al.*, Phys. Rev. C **80**, 034302 (2009).

[22] J. Endres, *et al.*, Phys. Rev. Lett. **105**, 212503 (2010).

[23] S. Ceruti (spokesperson), *et al.*, "Letter of Intent to the INTC I-194: Study of the Pygmy Dipole Resonance using an Active Target" (2017).