The PRESPEC liquid-hydrogen target for in-beam gamma spectroscopy of exotic nuclei at GSI

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Abstract

We report on a new liquid hydrogen target dedicated to in-beam gamma spectroscopy experiments in inverse kinematics at relativistic incident energies at GSI/FAIR. The target-cell and entrance window are composed of 200-μm thick Mylar. Target thicknesses from 10 to 60-mm can be reached for an effective diameter of 70 mm. The proposed design has the advantage of being free of absorbing material at forward angles and 90 degrees, allowing the detection of photons on a wide angular range. A commissioning experiment with a ^{54}Cr beam at 130 MeV/nucleon has been performed at GSI with the RISING setup. The target has been shown to behave as expected and is ready for experimental campaigns with AGATA.

Keywords:

1. Introduction

Exotic nuclei exhibit structure features that are different than those observed in stable nuclei, such as clustering at low excitation energy or a modified single-particle shell structure. The development of dedicated radioactive-beam facilities allows the study of these new phenomena. Unstable nuclei are produced either at relativisitc energies by fragmentation as in RIBF, RIKEN, and GSI or by the Isotopic Separation On Line (ISOL) technique as at SPIRAL, GANIL, or ISOLDE, CERN. Beam intensities available for the most

exotic species are typically 10^4 pps down to less than a particle per second. To counter-balance low beam intensities, the use of thick targets, when posible, is a straightforward way of increasing the luminosity. In this context, in-beam gamma spectroscopy at relativistic energies in inverse kinematics has been shown to be a powerful tool for the investigation of nuclear structure away from stability. Indeed, the combination of intermediate energies and detection of gamma rays allow the use of very thick targets, with the only restriction of reaching a sufficient energy resolution after Doppler-effect reconstruction. The in-flight-emitted gamma ray measurement requires the knowledge of the recoil velocity and the gamma emission angle to correct the Doppler effect and access to the gamma energy in the rest frame of the emitting nucleus. The efficiency of this correction relies on the accuracy with which we detemine these two quantities. The former depends on the granularity of γ ray detectors (size of Ge crystal) while the first is linked to the interaction point in the target. The use of a thick target increases the uncertainty on the interaction point position and therefore degrades the energy resolution.

Several reaction mechanisms and target combinations can be used at relativistic energies to discover the properties of unstable nuclei. Most commonly used, coulomb excitation and heavy-ion induced inelastic scattering experiments allow to investigate the collectivity of nuclei, whereas one nucleon knockout reactions have been used to populate single-particle states and test structure model wave functions through the comparison of experimental and theoretical cross sections. Among all possible material for the target, hydrogen offers unique advantages. It brings the possibility of using different reaction mechanisms with a unique selectivity: proton inelastic scattering (p,p') is sensitive to the neutron and proton collectivity, complementary to coulomb excitation, and proton-induced knockout reactions such as (p,2p) and (p,pn) are known to be the cleanest hadronic probe for spectroscopic factor extraction from knockout reactions. An additional benefit of hydrogen targets is the large number of scattering centers for a same energy loss in the target compared to larger-atomic-number targets, such as ^{9}Be or ^{12}C. By using an hydrogen target for in-beam gamma spectroscopy, the luminosity can be improved while containing the energy resolution. Another advantage of pure hydrogen targets is the background reduction. The breakup of heavy-ion targets may lead to the emission of neutrons and provoke background events in the measured gamma spectra. Furthemore, less bremsstrahlung contamination is expected when using a pure-hydrogen target compared to

heaviest-ion targets [**?**]. Consequently, a minimized signal over noise ratio in the measured gamma spectra can be expected.

For these reasons, liquid or solid hydrogen targets have been developed to study the nuclear structure all over the word, for instance at GANIL [**?**] and RIKEN [**?**], the available thickness ranging from few millimeters to several centimeters. A recent review of those different targets and applications could be found in reference [**?**]. In this context, a thick liquid hydrogen target has been developed by the cryogenic division of CEA. It is primarily dedicated to experiments with the AGATA [**?**] demonstrator at GSI and, in the future, to HISPEC campaigns with AGATA at FAIR.
In the following, the design of the target will be detailled in section 2 and operating modes will be described in section 3. In the design of the present target, particular attention has been focused on safety aspects which are summarized in section **??**. Results from a dedicated commissioning experiment at GSI are finally presented in section **??**.

2. Target design

The Magnetism and Cryogenics laboratory (SACM) of CEA-IRFU has developed expertise in cryogenic targets including liquid and solid hydrogen targets. Several targets have been designed for experiments at the Saturne Laboratory, Saclay, from 1985 to 1997 and since 1998 for the Jefferson Laboratory (targets for the POLDER and CLASS experiments), for the spalation program at GSI (FRS1, FRS2 and SPALADIN targets [**?**]) and, more recently, for upcoming low-energy experiments with radioactive beams at SPIRAL2 [**?**]. The present liquid target is based on the use of a cryocooler, limiting the amount of hydrogen in the liquefied active volume, enhancing the safety related to the use of hydrogen. Particular attention is applied to the target container itself, made of Mylar, whose thickness satifies an acceptable compromise between mechanical strength and transparency.

2.1. Overview

The installation is composed of two distinct parts (see Fig.1): the target and the control of the system. They can be separate up to 15 meters. The the target and its cryostat are installed in the experimental area. A cryocooler (cold head and compressor) is used to reach temperature of about 20 K.

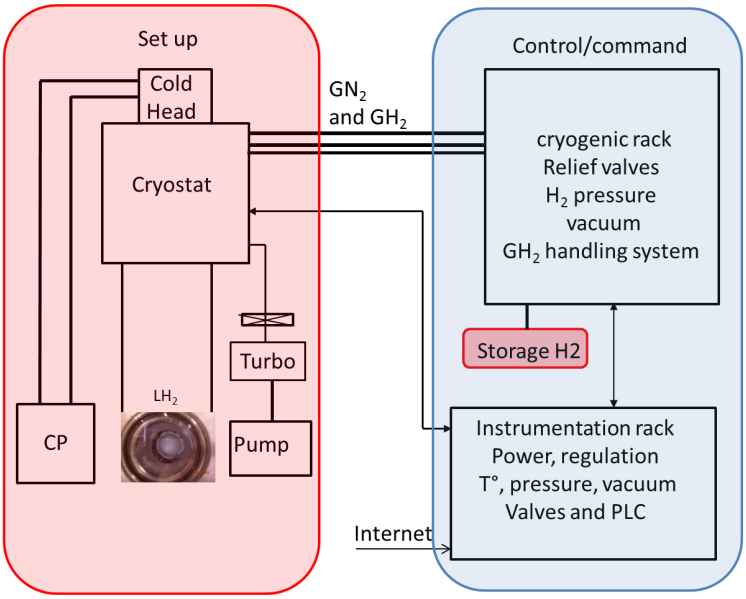


Figure 1: Synoptic of the system including (left) the target and cryostat and (right) the control-command.

The pumping system (turbo pump and primary pump) is located around the cryostat. A remote controle command is used to pilot all the installation and placed on the roof of the experimental room. It is composed of two racks: one is dedicated to cryogenics and the second to control temperature and pressure probes and valves. The gaseous hydrogen (GH_2) storage is connected to the cryogenic rack and the target. Different informations (vacuum, H_2 pressure or cryocooling) can be viewed via a computer interface. A dedicated Programmable Logic Controller (PLC) controls the system.

2.2. The target cell

The target cell is made of two components: (i) a Mylar entrance window (125 μm thick and 6 cm in diameter) is glued on a stainless steel body (with filling and return gas tubes) (see the right picture of Fig.); (ii) a Mylar exit window (150 μm thickness and 7.5 cm in diameter) formes the body of the target (see the left and middle pictures of Fig.). The cap were thermoformed at 160° by mechanical stamping. The two parts are gathered with an Helicoflex® seal. Elastic properties over a large range of temperature

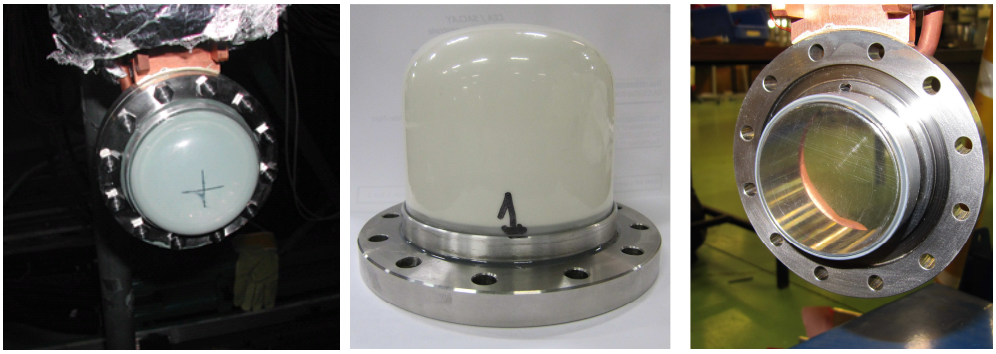


Figure 2: Target cell of the 20-mm thick target (left) and 20-mm target (middle). (Right) Entrance window of the target mounted on its flange.

of this Helicoflex® seal made of metal coated with aluminium ensured the impermeability of the cell.

These Mylar envelopes are built with a dedicated set of tools designed to obtain the desired geometry. The glue used is unique to withstand low temperatures (T 77 K) and remain flexible to overcome the differential shrinkage of the materials used at 20 K (Mylar, aluminium and stainless steel). The function of the glue is to ensure sealing between the different parts of the target. To strengthen pasting needed by the internal pressure efforts (maximum internal pressure is 1330 mbar absolute at room temperature), two aluminium rings are placed around the envelope of Mylar on the part of stainless steel. These rings help (by contracting at low temperature) the continuation of pasting. The Safety Manual of Fermi lab (ref?) recommends a burst pressure for Mylar flask of at least 2.8 bars (internal differential pressure). Results of three crash tests of the window and the container in Mylar are 9,3 bars for entrance window and 11,3 bars for the container, well above the widespread Fermi Lab safety rules.

2.3. The cryostat

The cryostat is mounted at the vertical of the target (see Fig. 3) on a support, designed in agreement with the experimental environment. For the commissioning experiment, the thermometry and the hydrogen and nitrogen connections of the circuits are on the top of the cryostat at 3,50 meters high above the ground. The compressor and the vacuum system were located on the floor. The cryocooler is composed of two flexible loaded with helium gas, connected between the compressor and cold head.
The cold head is on the top of the cryostat. Inside the cryostat (see Fig.3), the thermally insulated from the exterior is a copper shield cooled by contact with the first stage at 50 K. The condenser is mounted on the second stage of the cold head. It is a copper cylinder 8.7 cm long and 14.1 cm in diameter. Hydrogen is cooled and liquefied by contact inside it at 20.4 K. Liquid hydrogen formed flows by gravity to the target located in the lower part of the cryostat. The target is fixed by a support at the bottom of the condenser. The assembly is at liquid hydrogen temperature. The cold vapors contained in the return tube of the target liquefy again in the condenser (the coldest part of the cryogenic system). Then the liquid falls in the supply pipe of the target which remains full. By the principle of thermo siphon, the target is always supplied with liquid hydrogen.

2.4. Control and command

Piloting operations are conducted in the control command area. Cryogenic and instrumentations racks are connected together and to the cryostat. The cryogenic rack permits to introduce hydrogen (or deuterium) gas from the storage vessels to the target and also different processes like air emptying of the H2 circuit or vacuum chamber and the filling with N2 gas. There are manual valves, relief valves connected to discharge circuit, different manometers, two pressure sensors and one primary vacuum gauge. A fully automatic system piloted by the instrumentation rack permits the gas liquefaction. A drive flow indicates the amount of hydrogen that is liquefied in the cryostat.

The instrumentation rack supplies electrical power (low and high voltage). Several indicators give different informations : pressure, temperature, gas flow, vacuum of the cryostat and the H2 circuit. Automaton inputs/outputs are connected to the different instruments of this installation (compressor, pumps and a few valves) and all the informations given by the indicators.

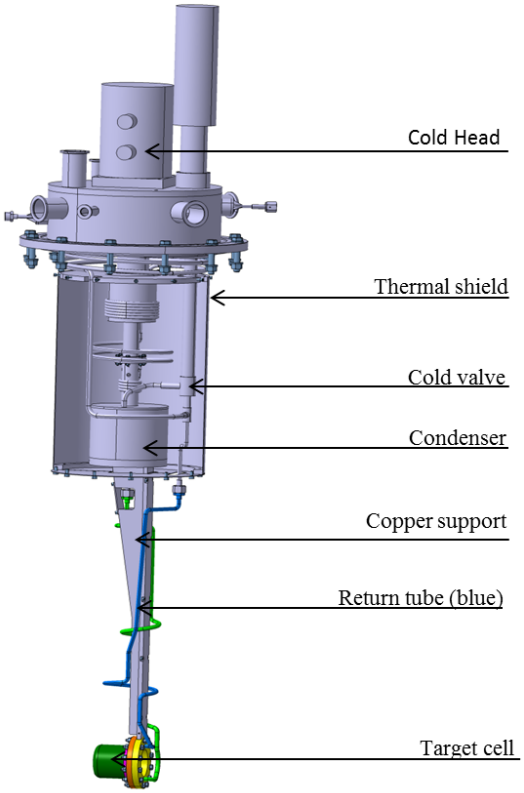


Figure 3: Global view of the cryostat and the target cell (in green).

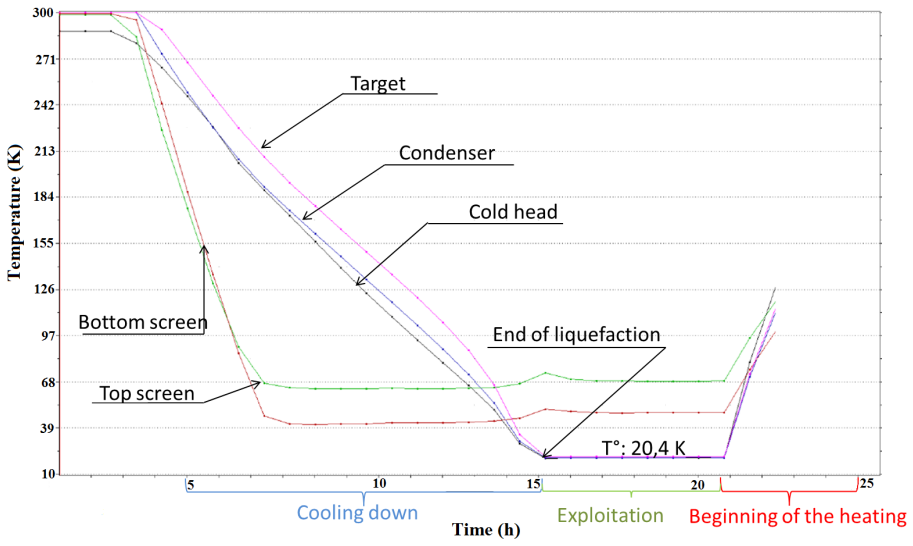


Figure 4: End of liquefaction

3. Operation modes

The installation has three working modes. Liquefaction mode during the cooling down and filling, Exploitation mode when the target is used for experiments and Stop Experiment mode during the target reheating and the gas return in the storage and the most important the securing of the cryostat by introducing N2 gas at the end.

3.1. Cooling

Liquefaction system is totally independent of the automaton. The gas flow is controlled by a proportional valve. The pressure set point during cooling down and liquefaction is adjusted to 1050 mbar (ABS). At the end of liquefaction, pressure transmitter of the H2 storage is adjusted to 1100 mbar (ABS). At this value, electro valve closes automatically (see Fig.4). After liquefaction a transient phase is inevitable during the pressure stabilisation. To avoid a liquefaction mode return, (gas returns through two relief valves to the storage) it will be necessary to close the electro valve.

3.2. Running

The automaton manages alarms by using the different set points necessary to secure a normal working. Most alarms are only indicative and without interaction with the operation. A few alarms activate automatic actions.

Note that the design of the system allows to empty the target in few minuts, often mandatory for background measurement and substraction to the data. The closing of the cold valve stops the thermo siphon process and the liquid hold in the target comes back and stays in the condenser because the pressure is higher than the condenser (3 to 5 mbar). The empty target is only filled with cold hydrogen vapor, i.e. of negligeable thickness compared to the entrance and exit windows.

3.3. Warming up

4. Safety considerations

Hydrogen is cooled and liquefied by contact with the second stage of the cold head. This configuration limits liquid volume to about 100 cm^3. The target and the refrigeration system are in an extra 100 litres vacuum chamber which provides a secondary containment volume in case of a target rupture. The target is connected to a 255 litres storage tank through two separate check valves. The exhaust from these valves will be evacuated outside through the safety exhaust line. The final pressure in the storage tank will be 1.05 bars (ABS). This eliminates any risk of explosion fuelled by oxygen leaking into the system. Filling the target with hydrogen requires about 84 litres of gas NTP. As a result, the initial pressure of the storage tank is 1.33 bars before the hydrogen liquefaction. The total amount of hydrogen used in the entire system is 340 litres of gas NTP. According to the Fermi lab regulations, storage and use of flammable gases at physics experiments, our system is classified as risk class 0 (hydrogen volume 7.4 m^3). This still does present some risk of potential explosion, so the system has been designed to be fail-safe and constitutes a totally closed loop with two levels of containment.

The basic idea behind the handling of any flammable or explosive gas is to remove oxygen and prevent exposure to an energy source that could cause ignition. The source of oxygen in the atmosphere and ignition sources are

electrical equipment. The following general guidelines are used for designing the gas handling system :

- no valves can open the system to air,
- each pressure monitor is spark-proof,
- the pumps used in the storage tank circuitry are leak-proof (hermetic).

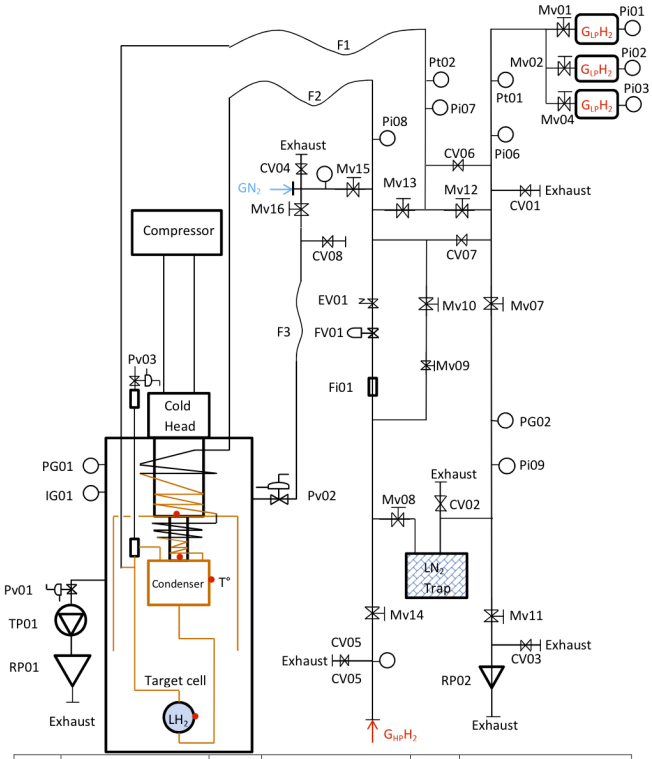
4.1. Handling of emergencies

In the case of a compressed air failure and/or electrical failure, the target is always connected to the storage tank via two relief valves (see Fig.**??**). The final pressure in the target is the initial pressure in the tank. Protection against blockage due to the solidification of a contaminating gas, such as air, in the H2 refrigeration circuit (no matter where the blockage occurs) is ensured since the entrance and return target lines are connected to pressure safety valves. During the transfer operation, the target condenser and cell are protected against blockage by the radiation shield which precools the gas to 40 K; all gases other than hydrogen will be trapped there.
The target temperature is regulated by automaton. In case of a regulation system loss there is a risk of a hydrogen solidification which could lead to target damaging. To avoid such a problem, the compressor is automatically stopped when the target pressure reaches a threshold value of 310 mbar (equivalent temperature 17K) which is given directly by the pressure transmitter.

4.2. Loss of vacuum in the chamber

Loss of vacuum in the chamber represents the highest level of emergency in the system because of potential hydrogen leak. The following actions are automatically realized:

- vacuum pump is stopped during cooling down phase,
- compressor is stopped,
- verify that manuals valves are closed (normal status) to avoid additional hydrogen coming from the storage tank. The gas will go back to the storage tank via pressure safety valves.



MV...	Manual Valve	TP01	Turbo pump	T°	temperatures
CV...	Check Valve	RP ...	Rough pump hermetic	$G_{LP}H_2$	Gas H_2 low pressure
Pt ...	Pressure Transmitters	EV01	Electro valve	$G_{HP}H_2$	Gas H_2 high pressure
IG...	Ion Gauge	FI01	Flow indicator	GN_2	Gas N_2 low pressure
PG ...	Pirani Gauge	FV01	Flow valve	LH_2	Liquid Hydrogen
Pv ...	Pneumatic Valve	Pi ...	Pressure indicator	F ...	Flexibles

Figure 5: the schematic diagram of the hydrogen circuitry.

4.3. Rupture of the target cell

First of all, there is a deposition of the flask contents into the vacuum space. The maximum pressure in the vacuum chamber and the storage tank will be respectively 0.84 bars and 1.05 bars. The residual gas in the vacuum chamber has to be evacuated manually with pump. (?)
In the case, very unlikely, of a simultaneously closing of storage tank manual valves and a target cell rupture, the maximum pressure in the vacuum chamber is always 0.84 bars. In any case, there is no need for check valves on the vacuum chamber to evacuate the gas as the final pressure is low enough. There is no risk to have a vacuum chamber failure.

5. Commissioning experiment

A commissioning experiment with a 20-mm thick target was performed to validate the whole system in experimental conditions. The target was inserted in the FRS beam line in the S4 experimental hall at GSI. The control command and hydrogen tanks for the target were located on the roof of the experimental area. A stable beam of ^{54}Cr at 360 MeV/u, limited to 400 000 particles/spill of 10 s, was produced by the accelerator complex UNILAC+SIS [**?**] and delivered at the hydrogen target at an energy of 126 MeV/u. Data were collected during 8 hours of beam time. The reaction products were identified by the calorimeter LYCCA-0 [**?**] (first stage of projectile-like residue identification for HISPEC experiments at FAIR). The energy loss and residual energy of projectile-like residues were measured with telescopes composed of DSSD and CsI detectors placed at 3.6 m downstream of the target. Two plastic scintillators positioned upstream and downstream the target (separated by 4 m) were used to measure the time of flight of the residues. 12 RISING triple clusters [**?**], each composed of seven Ge crystal, were positioned at forward angles in close configuration (700 mm from the target). A shielding composed of layers of lead and tin were placed in front of each cluster to reduce the low energy background in the gamma spectra.
The reactions products were clearly identified in atomic number by the standard ΔE-E method. The absolute mass determination was performed via the measurement of the kinetic energy of each projectile and his velocity after the target. A mas resolution of ΔA/A=1 was achieved during this test experiment.
On Fig.**??** are shown the energy distributions obtained for residues from the

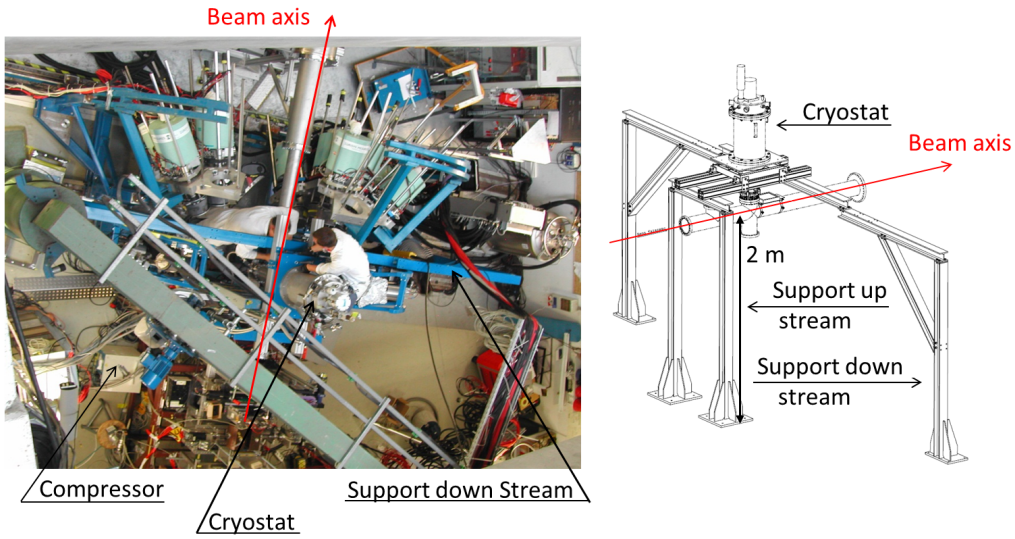


Figure 6: Top view of the experimental vault during the installation of the cryostat at the vertical of the target location. On this picture, the beam direction goes from top to bottom.

reactions of inelastic scattering *(a)*, knockout -1n *(b)*, -2n *(c)* and -4n-2p *(d)*. These distributions are obtained after a selection on the Ge time; only the edge of the peak in the Ge time distribution has been considered to overcome the γ rays coming from interactions of the beam with detectors placed either downstream or upstream the target. The γ rays detected by the crystals close to the beam line (θ_γ¿18°) have been excluded from the analysis, as for those crystals, the signal over background is small. The addback procedure has been done in those spectra, with no specific requirement on the gamma energy. We found that this correction improves the signal over background only for high energy transition ($E_\gamma \geq 1400$ keV). We obtained an energy resolution of 30 keV at 834 keV, close to the expected one of 26 keV calculated with GEANT4 simulations. In those spectra, signal over background is around 2, but reaches 3 at 1436 keV in ^{52}Cr.

We extracted exclusive cross sections for the population of ^{54}Cr (2^+ state), ^{53}Cr ($5/2^-$, $7/2^-$ states), ^{52}Cr (2^+, 4^+ states), and ^{48}Ti (2^+, 4^+ states). The corresponding Doppler-correctes gamma spectra are shown in Fig. **??**. The efficiencies have been given by GEANT4 simulations. The results are

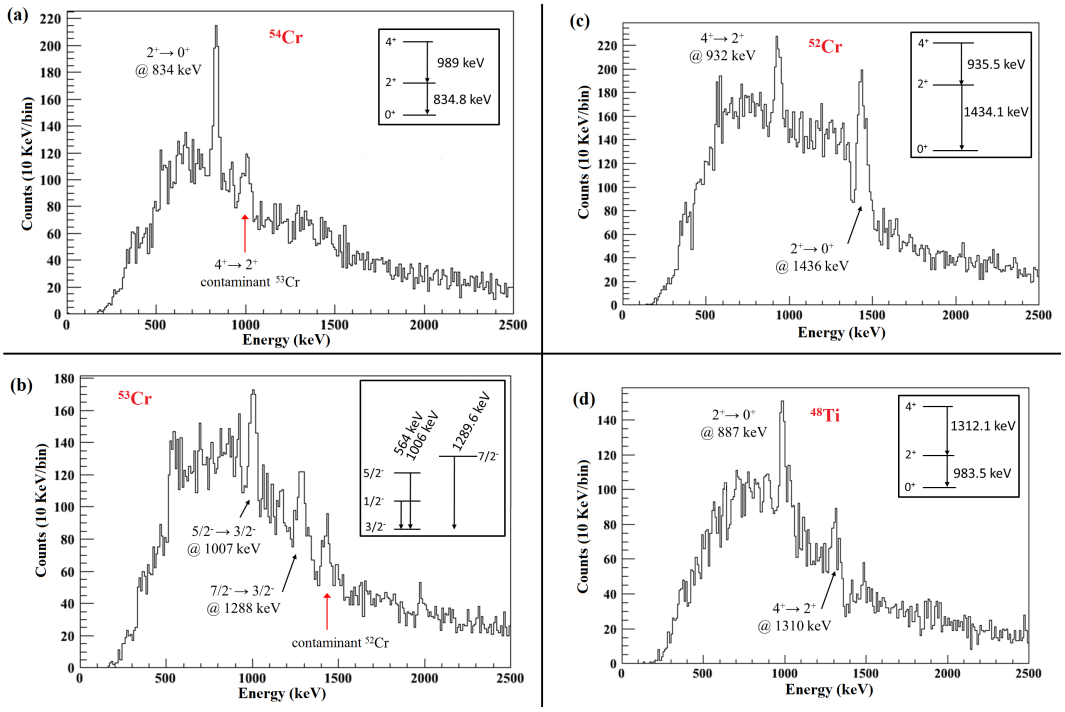


Figure 7: Gamma energy spectra in coincidence with (a) ^{54}Cr, (b) ^{53}Cr, (c) ^{52}Cr and (d) ^{48}Ti.

gathered in Table.**??**. Some theoretical predictions are also given in the table for comparison.

Table 1: Exclusive cross sections for ^{54,53,52}Cr and ^{48}Ti

i	σ^i_{exp}	σ^i_{theo}
2^+ of ^{54}Cr	.. mb	.. mb
$5/2^-$ of ^{53}Cr	.. mb	.. mb
$7/2^-$ of ^{53}Cr	.. mb	.. mb
2^+ of ^{52}Cr	.. mb	.. mb
4^+ of ^{52}Cr	.. mb	.. mb
2^+ of ^{48}Ti	.. mb	-
4^+ of ^{48}Ti	.. mb	-

6. Conclusion

A new liquid hydrogen target for in-beam gamma spectroscopy experiments with radioactive beams at GSI/FAIR has been built. The device is dedicated to proton-induced inclusive reactions at intermediate energies. The target is composed of a Mylar cell (typically 200 μm thick) with an effective diameter of 65 mm. The target thickness can be chosen from 10 to 80 mm. Today, two target cells have been conceived: 20-mm and 60-mm thick. The present target requires 12 hours to be conditioned from room temperature to operation mode. It can be emptied and refilled in few minutes for background measurements during the data taking. A commissioning experiment was performed by use of a ^{54}Cr beam at 126 MeV/nucleon. The data taking and the data analysis showed a proper operation of the full system.
The target is ready for in-beamm gamma experiments with the AGATA detector at GSI and, in the future, FAIR to explore the collectivity and single-particle shell structure through inelastic scattering and knockout, respectively.

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