CHYMENE, a thin windowless cryogenic hydrogen target

Introduction
Direct binary reactions with a light projectile and a heavy target have been for years a major source of information on nuclear spectroscopy. Light particles have a simple structure with no or few excited states. Moreover, the one-nucleon transfer is a rather simple peripheral process with a high selectivity. Thus, hydrogen-induced reactions, like the stripping reaction \((d,p)\), are of major interest since the reaction mechanism has to be well understood to obtain reliable structure information. In that case, the structure of the heavy partner may be properly determined, with little sensitivity to ambiguities due to the nuclear potentials. Due to the nature of the reaction, there is a limitation to the incident beam energy corresponding to the nucleon transferred from one to the other nucleus. A too large incident energy would result in no transfer cross-section.

With the recent development of radioactive beams, it is now possible to study exotic nuclei in a similar way: inverse kinematics is used with a heavy projectile and a hydrogen target. The inverse kinematics has stronger effects with increasing mass of the projectile: the ejectile is focused in a narrow angular range around zero degrees. Due to the finite resolution of the detectors, the angular resolution in the centre of mass frame is rapidly insufficient to determine the angular distribution of the process when only the heavy partner is measured. The detection of the light recoiling particle may be a solution, whenever its energy is large enough to escape the target. This is also a reason why targets heavier than hydrogen or helium are generally not used. More specifically, the detection of the recoiling nuclei is the only way to measure unbound states in direct reactions. Recently, high performance detector arrays have been developed in order to detect these light recoiling particles with a silicon technology. A great expertise has been developed in SPhN with the MUST and MUST2 arrays mainly used at Ganil so far. The energy resolution depends strongly on the thickness of the target, especially for low energy recoiling particles. To improve the resolution, high resolution photon spectrometers like EXOGAM at Ganil (or AGATA in the future) may be used. Magnetic spectrometers like SPEG or VAMOS are the needed complementary tools of such a detection set-up.

Hydrogen targets (proton and deuterium) are used to perform elastic-inelastic scattering \((p,p')\) or \((d,d')\), or nucleon transfer reaction like \((p,d)\), \((d,p)\), \((d,^3He)\), etc… Nuclear spectroscopy studied by nucleon transfer reactions is expected to be one of the major field of interest for the SPIRAL2 facility, soon available at GANIL, as detailed in [1]. These reaction mechanisms are the main tools used by the exotic-nuclei group of SPhN to study nuclear structure of exotic nuclei. The SPhN gamma-spectroscopy group is also planning to use transfer reactions and proton inelastic scattering to complement its research programme [2].

A very common choice for hydrogen targets is polypropylene foils \((CH_2)_n\) or \((CD_2)_n\) for the simplicity of use and control of homogeneity and thickness. However, compared to a pure hydrogen target, the presence of carbon atoms is a severe drawback in three aspects:

(i) for the same energy loss of the projectile and reaction products in the target, the effective thickness of hydrogen is 4 times less in a CH\(_2\) target than in a pure solid hydrogen target,

(ii) the carbon atoms are responsible for a background which has to be removed via dedicated beam time with a pure carbon target, which is obviously a reduction in the beam time available for experiment.

(iii) the larger energy and angular straggling of reaction products in the CH\(_2\) target, which deteriorates the resolution of the measured energy spectra.

These three drawbacks are strong limitations when one is concerned with high-Z, low-energy and low-intensity beams, as neutron-rich nuclei expected from the SPIRAL 2 facility.

Cryogenic hydrogen targets have been already developed and used in experiments for nuclear physics. As examples, let us mention:

(i) at Riken, a windowless 3 mm thick target is available [3], well adapted for incident energy around 80 A.MeV, but much too thick for experiments below 15 A.MeV (fig.1, left). Moreover, due to the
manufacture, the homogeneity (or even the breaking strength) may be a problem for decreasing thicknesses;

(ii) at Ganil, a solid 1 mm thick hydrogen target (fig.1, right) has been used at 10 A.MeV [4]. It is still too thick for low energy reactions, with the additional drawback of 4 Mylar foils. They may be seen as secondary targets, like in the case of a (d,t) transfer contaminated by (p,d) in the foils leading to the same final nuclei [5].

![Fig.1: (left) a solid windowless target done between two bellows, removed when the target is frozen; (right) a solid hydrogen target, 1mm thick. The helium gas is evacuated after solidification of the target, but the four Mylar windows remain.](image)

In any case, it is an open challenge to obtain a windowless pure hydrogen target thinner than 1 mm. Even if the mechanical aspects would be resolved, another problem has to be overcome due to the residual gases in the vacuum chamber. The vacuum has to be maintained at a very low level, better than $10^{-6}$ mbar, to avoid the deposit of contaminants on the cold surface of the target. For long working periods, the quality of any static cryogenic target is not guaranteed, especially when thinner targets are concerned.

**Objectifs**

The future SPIRAL 2 facility will deliver neutron-rich fission products accelerated at energies ranging from 5 to 12 MeV/nucleon. Due to the range of large Z nuclei in hydrogen at SPIRAL2 energies, pure hydrogen targets can only be used if their thickness is reduced below 1 mm. Experimental efforts have to be done on new innovative technologies and we propose to develop a windowless pure hydrogen target with a thickness that may be varied continuously from 1 mm down to 100 µm. Moreover, the target will not be static; it will consist in a hydrogen film squeezed out an extruder device in a continuous motion given by an endless screw. In the vacuum, the hydrogen film will interact with the beam and will be rapidly evacuated afterwards. As the target is continuously renewed, it is little or not sensitive to the contamination due to residual gases even for a very small thickness.

A target thickness larger than 1 mm is not excluded by that technique, so that the use of such a device would not be restricted to Ganil and the Spiral 2 facility, but could be used in other laboratories where beams at higher incident energy are available like RIKEN or GSI.

The project is dedicated to hydrogen targets as a first priority. However, that technique may be applied a priori to other gases, although in each case a specific study has to be done. This may also be a solution for elements for which a conventional target cannot be done.

In conclusion, the project CHYMENE (Cible d’HYdrogène Mince pour l’Etude des Noyaux Exotiques) will provide the nuclear physics community with a pure thin hydrogen target, which will optimize the use of the SPIRAL2 beams at low incident energy. In conjunction with existing state-of-the-art detection set-up, it represents a remarkable move forwards in the study at SPIRAL2 of nuclear structure by direct reactions in inverse kinematics.
**Description of the project**

Cryogenic targets $\text{H}_2$ or $\text{D}_2$ are feasible with existing techniques as long as the thickness is larger than 1mm. However, for heavy ion beams at low incident energy, targets thinner than 1mm are needed. In that case, the thickness of the target is low compared to its size, so that the control of the freezing phase (and so the homogeneity) may be a problem to avoid bubbles or fractures. The homogeneity is also reduced when the thickness locally varies. For that reason, we need a constant overall thickness from the center to the edges of the target, which means parallel faces. Finally, Mylar windows are often necessary but they may be considered as secondary targets with protons and carbon atoms. The target over windows thickness ratio becomes very unfavourable when we try to reduce the thickness of the target.

As an example, we recently used a cryogenic solid $\text{D}_2$ target with a thickness of 1mm (17 mg/cm$^2$) with four mylar foils and a total mylar thickness of 3 mg/cm$^2$. This was not a problem as we studied the stripping transfer reaction $^{26}\text{Ne}(\text{d},\text{p})^{27}\text{Ne}$, but in the case of the pick-up transfer, the $(\text{d},\text{t})$ channel is in competition with $(\text{p},\text{d})$ and the same final nucleus $^{25}\text{Ne}$, making the analysis more difficult. [6]

- A very original technique has been recently developed: the hydrogen (H$_2$ or D$_2$) is used in an amorphous non-crystalline solid phase at the entrance of an extruding nozzle. With a temperature gradient between the entrance and the exit of the nozzle, the hydrogen ice is continuously pushed out of the nozzle, with the lowest temperature just at the exit of the nozzle.

A picture of such a device is shown in fig.2. In that case (taken from [7]), a piston is used to push the hydrogen ice out of the nozzle.

The DSM/DRFMC/SBT in collaboration with the PELIN laboratory in St Petersburg are the European leader in these techniques for which they have developed a great expertise.

The main goal of the PELIN laboratory is the development and production of injectors for plasma fuelling of thermonuclear devices with magnetic confinement. The fuel is supplied into the plasma of operating thermonuclear devices from the injectors in the shape of solid hydrogen or deuterium pellets within limited time (several seconds only). Due to new technologies and know-how developed by PELIN, it became possible to inject fuel in steady-state mode for a long time (more than 2000 sec), as it is required by the prospective thermonuclear power plant.

The injectors produced by PELIN are mounted on the world’s largest stellarator LHD (Japan), on the TORE SUPRA tokamak (France) since 2004 with the longest plasma discharge, on the HT-6L tokamak in China, on the T-10 tokamak (Russia). A new pellet injector with a screw extruder is now being developed for JET tokamak and will be installed during summer 2007. Pellet injectors for LHD and TORE SUPRA, shown in Figures 3, use the unique technology of solid hydrogen screw extrusion, developed and patented by PELIN for the first time in the world.

In the screw extruder, hydrogen undergoes continuous freezing and is squeezed out of the extruder as an ice rod, which is then cut into pellets. The pellets are accelerated by high-pressure gas and fed into the plasma of fusion devices at a velocity of 200-1000 m/s. A transparent solid hydrogen rod for pellet formation is shown in Fig. 3.
Fig. 1: design of an extruder device for the fabrication of a deuterium ice, with two stages: in the first one, the hydrogen is in a liquid phase, in the second in a non-crystalline solid phase to allow the final extrusion in the nozzle. The coldest temperature is obtained at the exit of the nozzle.
Fig. 2: Pellet injector with a screw extruder installed on the TORE-SUPRA (France)

Fig. 3: A transparent solid hydrogen rod (in the centre of the yellow zone) extruded from a screw extruder.
In these cases the ice is a rod with a rectangular shape of 1mm *3 mm and a length of 3 mm to a shape of 6*6 mm and a length to 6 mm. We are very confident for the fabrication of a new prototype to produce thin hydrogen films. The knowledge of this technology allows to reduce the research and development cost. So the efforts can be pushed to the physical aspect of the project which is the main goal.

- There will be a study phase for the design of an extrusion nozzle in order to obtain an hydrogen film with a thickness which can be varied from 1mm down to 100 µm. Even if the technology is completely under control and sub-millimetric thicknesses appear to be a straightforward extension of the existing applications, what will be the exact minimum thickness to be obtained with that technology is still to be determined. The width of the film will be about 1cm. In the technology developed by partner 2 and the PELIN laboratory, the piston shown in fig.1 is replaced by an endless screw. The advantage of the screw extrusion technology is that it will ensure a continuous refuelling of the target.

The fact that this technology does not need any Mylar window represents a unique advantage relative to existing devices. A thickness larger than 1 mm may also be considered and studied.

- The second phase of the project will be the integration of the extruder in the context of an experiment, especially in the vacuum of the reaction chamber. All the partners will be involved in this task. The distance between the exit of the nozzle and the beam axis is an important parameter that has to be studied. In any case, it should be as small as possible. Another related parameter to be studied is the flow velocity of the target. After interaction with the beam, it is crucial to evacuate the hydrogen film. With that technology, any low frequency vibration which affects the film even after the irradiation may have consequence back at the beam level. For that reason, we may consider to cut the film after irradiation and evacuate it with an appropriate pumping station to remove it from the interaction area between the beam and the target. All that procedure has to be done in the vacuum of the reaction chamber which has to be preserved at a very high level ($10^{-6}$ mbar) to avoid contaminations on the cold target.

Around the target, light charged particle detectors inside the vacuum chamber and photon detectors outside the chamber have also to be integrated. That means that the space around the target has to be carefully studied in a design study to avoid as far as possible materials in area dedicated to particle measurement. Especially for light charged particles emitted in direct reaction in inverse kinematics, the forward and backward hemisphere should be kept free for material as far as possible. Also for photon angular distribution, it is necessary to be able to use some detectors at 90° relative to the beam axis. A compromise has to be found between the need for detection and the need for cold screens at nitrogen temperature to isolate the target from the thermal radiation (the vacuum chamber is more or less at ambient temperature).

It is important to foresee the rotation of the target in the horizontal plane. Depending on the kinematics of the reaction, it may be very important to measure particles emitted at or near 90 degrees relative to the beam axis, this is the case for (i) light charged particles in elastic scattering, (ii) photons when the asymmetries 90°/180° and angular distributions are measured. This measurement cannot be done when the target is perpendicular to the beam due to the target holder or(and) target thickness. For such a measurement, the target is rotated by 45°, so that the measurement at 90° is possible in the reaction plane. It is necessary to evaluate the best solution for that rotational degree of freedom.

Finally, an important part of the project will consist in the remote control-command of the whole device, for which we will take advantage of the expertise of the DAPNIA/SIS. Several points have to be controlled on line: pressure, temperatures, flow velocity, rotation of the target, etc... as well as all the safety aspects induced by a hydrogen target in a vacuum chamber connected to an accelerator. SIS is able to integrate a full control-command device on-line as well as a remote control via internet. In these conditions, the user will obtain a quick and efficient support, wherever is run the experiment. Typical examples of such devices may be found at CLAS DVCS (JLAB, USA); also the CO₂
analyzing device at Hanle (Cashmere). The liquid hydrogen target of the SPALADIN experiment at GSI (Darmstadt) will also benefit from this remote control-command. Moreover, the safety document of the SPALADIN target has been drawn up by DAPNIA/SACM belonging to the CHYMENE collaboration.

- A third task will consist in the determination of the target characteristics: thickness and homogeneity, and their evolution in time. The target thickness is a key aspect of an experiment since it scales the cross section. The task, under the responsibility of DAPNIA/SPhN, will be divided in two parts:
  (i) determine the thickness of the target in the characterisation phase. A dedicated measurement will be done with an energy-loss measurement of a proton beam with and without target.
  (ii) develop a technique to measure on-line the thickness of the target. Different methods will be investigated:
    - an energy-loss measurement of a beam charge state measured in the focal plane of a magnetic spectrometer like SPEG or VAMOS at GANIL,
    - an energy-loss measurement of a monochromatic electron beam passing through the target
    - detection of emitted hydrogen X-rays due to the interaction of the beam with the target.
An overall precision of ± 5% in the thickness measurement is needed. The method(s) chosen will be integrated, if necessary, in the whole environment of the experiment, so that the thickness will be measured on line during all the beam time. This will be the object of a postdoctoral position for which a funding for twelve months is asked in the ANR proposal.

References