Nuclear physics experiments with a windowless supersonic gas jet target

J F Favela, D Shapira, E Chávez, M E Ortíz, E Andrade, O G de Lucio and A Huerta

1 Instituto de Física, Universidad Nacional Autónoma de México, México, D.F. 04510, Mexico
2 Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
E-mail: ffavela@gmail.com

Abstract.
A new windowless gas target has been developed in Mexico. It is a supersonic gas jet flow produced inside a vacuum chamber which can be coupled to a regular beam line in an accelerator laboratory as a differential pumping system brings the pressure of the gas target system down to a microTorr, or better, at the connecting stage.

In this work, we present the system as it was designed and constructed as well as the first results using air, Nitrogen and Argon.

1. Introduction
Nuclear data (reaction dynamics, structure) becomes harder to obtain when experiments have to be performed with accelerated particles impinging on nuclei that are found in nature as gases. Sometimes it is possible to produce a solid compound that would contain the nucleus of interest (Hydrides for instances to study reactions on H), or build gas cells with thin windows for noble gases. These and other strategies may not always be appropriate because of the interference of the other materials present in the compound or the windows. It can also be unappropriate because the target may have low density as in the case of windowless gas targets. Gas jets are an optimal solution. In the present work a new facility developed for the Carlos Graef Fernández Laboratory of the Physics Institute at UNAM (CGFL) is described in detail. The CGFL is a facility powered by a CN-Van de Graaff accelerator. This machine provides light ion beams with energies up to $5.5\, MeV$, ideal for low energy nuclear physics studies. First data on different jets (Air, N, Ar) is presented.

A high density and spatially well defined gas film constitutes an ideal target for low count rate nuclear physics experiments, since they can sustain several orders of magnitude more beam intensity than a solid target without being altered. Such a gas target can be produced by a supersonic jet injected in the reaction chamber in vacuum.

Nuclear studies can be carried out on some gas substances by producing a chemical compound that is solid. Such is the case, for instances, of studies on Hydrogen, where it appears in the target as part of a molecule. In those cases, high intensity beams can change the Hydrogen content in the target as a function of time, and eventually destroy it. Also beam interactions with the other components of the molecules have to be taken into account.
Some gases cannot form molecules (noble), gas cells have been used to contain a certain amount of gas in the path of the beam. There the solid windows used to isolate the gas from the vacuum of the accelerator beam line limits the beam intensity as well.

The supersonic gas jet strategy to produce a target of a material that is found as gas in nature to be bombarded with accelerated particles is not new. An example of such devices made in the past can be found here [1]. An example of modern supersonic gas jet systems has just been finished at the University of Notre Dame in the USA [2]. The needed general theory can be found in [3] and [4].

In section 2, our device is presented in detail. Section 3 shows the results of the characterization of the windowless supersonic gas jet target. Some conclusions can be found in section 4.

2. Experimental Methods

Figure 1. (a) Shows an artistic representation of the gas jet: a high density gas column with a well defined frontier surrounded by high vacuum, (b) shows the jet target getting hit by the accelerator’s beam, notice the faint purple glow. The image is superimposed with part of the experimental array for better reference.

In figure 1 (a), a representation of the jet target is shown as a column of gas without walls. Also shown in the figure (b) a photograph of the accelerator’s beam hitting the jet target, which causes the jet area to glow. In this experiment 450 keV protons where used with a current of 1.5 μA. More details are also shown, the gas jet comes out of a rectangular nozzle (top) and is immediately caught by a pipe (bottom) connected to a powerful vacuum pump. Both the nozzle and the pipe are mounted in a way where they can rotate and their relative height can be adjusted.

For the experiments reported here a rectangular shape was chosen for the nozzle. The gas jet produced resembles a planar target and we can be adjust its density by simply rotating it. Nozzles of different shape are available and are easy to change.

In order to characterize the properties of our gas jet, experiments were made with air, Nitrogen and Argon. Gases that are non corrosive, toxic or explosive. Argon and Nitrogen are also nearly mono-isotopic elements in nature.

In figure 2, the experimental setup inside the scattering chamber used for the characterization of the target using Rutherford Back Scattering is shown schematically. The rectangular boxes represent charged particle detectors, one of which is shown in the superimposed image, figure 1 (b).
Gas is injected into the system at high pressures: 1-5 atmospheres. The pressure in the region surrounding the jet is of the order of 0.1 Torr meaning that it is too high for connecting to the accelerator’s beam line that is kept at high vacuum ($10^{-6}$ Torr or better). In order to connect the system a differential pumping system is needed, lowering gradually the pressure from the scattering chamber to the accelerator. In figure 3 an outline of the system is shown.

The chambers following the scattering chamber (jet chamber), are called the differential pumping system. Each are connected with their adjacent chamber via a small aperture, big enough to allow the beam go through but small enough to limit the throughput of gas from one chamber to the neighboring ones. The first and second chamber next to the gas jet chamber are pumped down by twin diffusion pumps (1200 l/s) while the last chamber, just next to the accelerator’s beam line, is pumped down by a turbo-molecular pump (400 l/s).

Using this system we are able to get the pressure in the turbo pump chamber down to the order
of low $10^{-6}$ high $10^{-7}$ Torr when we use air. Good references for calculating gas throughputs are [5] and [6].

Most of the pieces used in the system are ISO vacuum standard (QF and LF components), this is an important improvement from systems like this from the past (D. Shapira et.al. [1, 7], G. Bittner et. al. [8], Becker et. al. [9]) in the sense that it can be built and modified relatively quick. The used pieces are from the standard sizes LF250 (scattering chamber), LF200 (differential pumping system), LF100 (central jet pump), QF40 or QF25. And they where used from blank flanges to crosses, tees, hoses etc.

This allowed us to build the system quickly and minimized the need for special pieces. Some special pieces were needed anyway, for example, the inner walls in each chamber connect from both sides to a LF200 flange, the screws in the clamps were simply replaced with larger ones. For the apertures, a standard QF40 flange was used, and we can change the aperture size and shape simply by connecting a different QF40 flange.

Another example is in the scattering chamber, where we replace an LF250 blank flange with a special one (a nose flange) designed so that we are able to get a germanium detector as close to the jet as possible, and also allow us to place some lead shielding around the detector.

3. Results and discussion

3.1. RBS scattering

The experiments where performed with protons at various energies. And as mentioned before, Air, Nitrogen and Argon where used as the gas target. In the case of Nitrogen and Argon, the back pressure is the pressure measured from the gas bottle, 1-5 atmospheres.

The RBS data from the 2 charged particle detectors was symmetrical in all of our experiments. For our first experiment air was used, we simply opened the valve of our nozzle to admit air at atmospheric pressure ($\approx 600$ Torr).

The data is shown in figure 4. We were able to identify the various elements by their respective peaks, being the most representative the Nitrogen and the Oxygen peak.

Additionally there are a few more things to notice, one is the background. It is mostly shown in the channels before the peaks, therefore at energies below that of scattered protons.

We attribute this to the fact that there is poor vacuum in the area that surrounds the jet. So the beam actually starts scattering before it reaches the high density region of the jet. We expect that better collimation of the monitor detectors should eliminate this.

There is a small peak, more or less well defined, right behind each of the main ones (Nitrogen and Oxygen). In figure 4 we also show a zoom on the small peaks. The origin of these peaks is unclear. Since in this experiment we did not set up a set of collimators that would insure that
Figure 5. (a) 1.3\text{MeV} protons with Nitrogen target, (b) 2.8\text{MeV} protons without jet, (c) 2.8\text{MeV} protons on Nitrogen at 3.5 bars in back pressure (measured from the gas bottle), (d) count curve for 425keV protons at various target pressures.

Particles being detected come from the beam-jet interaction region, there is room for unwanted and exotic scattering events.

Table 1 shows a comparison of the data obtained via the RBS technique vs the reported percentages. A software package called SIMNRA [10] was used for aid in the analysis.

| Peak         | SIMNRA | reported |
|--------------|--------|----------|
| Nitrogen     | 77%    | 78.09%   |
| Oxygen       | 23%    | 20.95%   |

In figure 5 (a), we used 1.3\text{MeV} protons in Nitrogen and the peak can clearly be seen. Additionally we performed an experiment without the jet (figure 5 (b)), 2.8 \text{MeV} protons where used. The count rate was too low and most of the counts where in the low energy channels. So there is a clear difference between the jet with a high density profile and a thick gaseous target represented by the gas in the entire scattering chamber, since it is not perfect vacuum (for more info on simple gas targets see [11]).

From figure 5 (c), we can observe that:

- The main, Nitrogen, peak is well defined.
- The background, while is still non zero, it is well below the count rate of the main peak.
- A back peak can be shown in this case also (barely).

Figure 5 (d) shows the spectra of 425keV protons back-scattered from an Ar gas jet target produced using three different inlet pressures: 1, 2 and 3 atm. The first noticeable feature that can be seen in the figure is an energy shift or the peak as the inlet pressure is increased. This implies that the pressure in the system increases as more gas is injected in the system producing...
a larger energy loss in the protons. On the other hand, it can be seen that the thickness (areal density) of the target indeed increases as the inlet pressure does, as the peaks widen progressively.

3.2. Gamma experiments
To proceed with experiments where gamma rays are detected, we removed one of the solid state detectors and replaced a side flange of the scattering chamber with a special “nose” flange as shown in figure 3, designed specifically to minimize the distance between the interaction region beam-gas jet target and a germanium detector.

Firstly we measured the background over 24 hours at the lab in the final configuration, that includes some lead shielding. The two main peaks where identified as Potassium 40 and Thallium 208. Then the experiment was a proton beam on an Argon gas target (3 atm) with .

The beam energy was 425 keV as we ran as a parasite from a low energy astrophysics (p+C) experiment.

We were able to notice various peaks, mostly at energies higher that 1.5 MeV. As can be shown in figure 6 (a).

One of the regions of the spectrum where we see an excess yield, relative to the background spectrum, corresponds exactly with the 208Th peak. There seems to be also a significant excess of counts in the 1.7 MeV region, as shown in the expanded regions, figure 6 (b) and (c).

It has to be said that the proton energy was much lower than the Coulomb barrier and even smaller than the Gamow energy for stars at one billion degrees temperature. More experiments are planned to be made at higher proton energies to have a clear identification of the gamma rays from the capture reaction of interest to follow them at lower energies.

4. Conclusion
A new supersonic gas jet target facility has been designed, constructed and tested at the "Universidad Nacional Autónoma de México" in the "Instituto de Física", in the "Carlos Graef Fernández" Laboratory to be used in experiments with charged particle beams provided by a 5.5 MV CN-Van de Graaff Accelerator.

In this work, the first experiments where presented showing preliminary but coherent evidence of the good performance of the system. Three different gases at several pressures were used in these tests.

It is important to notice that the RBS experiment, with a windowless pure air column, showed a close match to the expected percentage of Nitrogen and Oxygen in air.
The system is functional, the pressure readings, the picture of the jet getting hit by the beam (figure 1(b)), the RBS data and the gamma spectrum where only a set of tests to the system. The modular design of the system is such that it can be improved or modified easily. This gives us the freedom to change, for example, the scattering chamber without touching the differential pumping system.

These features will be of much use when we upgrade it. An important improvement to come is a recirculation system, this will allow us to work much longer with much more expensive and, in general, dangerous gases.

Additionally we intend to increase the amount of charged particle detectors in the area surrounding the jet. As well as improvements to the RBS setup, that include the use of collimators, in order to clean the spectra.

Acknowledgments
This work was supported by CONACYT 82692, PAPIIT IN-118310, the shop at IFUNAM and Dr. Roberto Gleason’s support for the improvement of our facility.

References
[1] Shapira D, Jr JLCF, Novotny R, Shivakumar B, Parks RL, Thornton ST. The HHIRF supersonic gas jet target facility. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 1985;228(2–3):259 – 266. Available from: http://www.sciencedirect.com/science/article/pii/0168900285902670.

[2] Kontos A, Schürmann D, Akers C, Couder M, Görres J, Robertson D, et al. HIPPO: A supersonic helium jet gas target for nuclear astrophysics. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2012;664(1):272 – 281. Available from: http://www.sciencedirect.com/science/article/pii/S0168900211019899.

[3] Ackroyd JAD. Fluid mechanics considerations in supersonic jet target design. Science Research Council, DARESBURY LABORATORY; 1975.

[4] Pritchard PJ. Fox and McDonald’s Introduction to Fluid Mechanics. John Wiley & sons; 2011.

[5] Roth A. Vacuum technology. Second edition ed. North-Holland Physics Publishing; 1986.

[6] Lewin G. An elementary introduction to vacuum technique. American Vacuum Society monograph series. 1987;.

[7] Shapira D, Campo JGD, Jr JLCF, Shivakumar B, Stelson PH, Harmon BA, et al. Nuclear physics experiments with the ornl-hhirf supersonic gas jet target. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 1985;10–11, Part 1(0):436 – 440. Available from: http://www.sciencedirect.com/science/article/pii/0168583X8590285X.

[8] Bittner G, KRETSCHMER W, SCHUSTER W. A windowless high-density gas target for nuclear scattering experiments. Nuclear Instruments and Methods. 1979;167:1–8.

[9] Becker HW, Buchmann L, Görres J, Kettner KU, Kräwinkel H, Rolfs C, et al. A supersonic jet gas target for γ-ray spectroscopy measurements. Nuclear Instruments and Methods in Physics Research. 1982;198(2–3):277–292. Available from: http://www.sciencedirect.com/science/article/pii/0167508782902654.

[10] Mayer M. SIMNRA, a simulation program for the analysis of NRA, RBS and ERDA. In: American Institute of Physics Conference Series. vol. 475 of American Institute of Physics Conference Series; 1999. p. 541–544.

[11] Baca AM. Blanco de gas sin paredes para reacciones nucleares. Tesis para obtener el título de físico, U.N.A.M. Facultad de ciencias, México D.F.; 1964.