Stopping energetic heavy-ions in one-bar helium.

L. Weissman, P.A. Lofy and D.J. Morrissey.

National Superconductive Cyclotron Laboratory and Dept. of Chemistry, Michigan State University, East Lansing, MI-48824

(November 4, 2002)

Abstract

Various tests for stopping energetic, 100-150 MeV/amu, heavy ions in a 50 cm gas cell filled with helium at 0.5-2 bar pressure were performed. The fraction of ions stopped in the gas was measured as a function of beam energy degradation, gas pressure and position within the gas cell. Information on the range distribution was obtained and the residual energy distribution of ions was measured under different conditions. The experimental results are in good agreement with stopping power calculations in the literature. The experimental results are discussed in the context of the proposed RIA facility.

Typeset using REVTEX

24.10.Lx, 34.50.Bw

Key words: stopping ions, gas-cell, stopping range, range straggling

I. INTRODUCTION

Stopping energetic ions in gaseous helium with prompt extraction and cooling via collisions with helium atoms is considered a key element for the next generation of radioactive beam facilities [1]. Furthermore, the implementation of gas catchers at the existing fragmentation facilities can provide high-quality low-energy beams of short-lived radioactive ions that will significantly expand the range of possible studies. The IGISOL (Ion Guide Isotope Separator On-Line) technique has been used for more than 15 years to collect recoiling reaction products at low energies [2]. Currently several groups around the world are working on projects to stop energetic beams in gas catchers [3–5]. The results of an early experiment performed at the National Superconducting Cyclotron Laboratory (NSCL) were reported in [6]. At present a new gas cell catcher is being developed at NSCL as a first step of the Low Energy Beams Ion Trap (LEBIT) project [7], where the extracted high-quality low-energy ion beams will be utilized in precision experiments with an ion trap.

Stopping energetic ($\approx$ 100-150 MeV/amu) ions within a limited volume of helium (helium is used to retain the ions in the 1^+ charge state) is a challenging task. A 50 cm long gas cell filled with helium at 1 bar has an effective target thickness of about 10 mg/cm^2. In order to stop ions in such a thin target, two conditions have to be fulfilled: first, the beam energy has be degraded to a value of a few MeV/amu; and second, the straggling in the beam energy distribution from the energy degradation has to be minimized. The collection of nuclear reaction products that have a broad momentum distribution of energy before the slowing down process will be even more difficult and will require compensation for the energy spread in an ion-optical system with a special energy degrader [8].

The stopping of energetic primary ions in gas after energy degradation was demonstrated in [6] where transmission of ions in gas was measured as a function of gas pressure and compared with calculations. It was found that the homogeneity of the energy degrader and initial energy spread of the beam are of critically important for efficient collection of energetic ions. In this report we provide the results of tests for stopping energetic primary beams from the NSCL in a 50 cm gas cell. Special efforts were made to ensure the homogeneity of the energy degrader and the entrance window of the gas cell. The reported tests are performed for primary beams that have a very small spread in the initial momentum distribution.

II. EXPERIMENTAL SETUP.

A schematic diagram of the experimental setup is shown in Fig. 1. The beam line was tuned to produce a dispersive image in the horizontal plane at position A and to produce an approximately parallel beam into the gas cell. The beam energy was degraded in a set of borosilicate glass plates that could be tilted in the horizontal plane. The computer controlled drive holds six pairs of the plates (90 mm horizontal × 30 mm vertical) with thicknesses in the range from 1 to 3.6 mm. The glass plates were polished to be optically flat with nominal flatness of 1-1.5 μm. The density of the plate material was measured and found to be 2.506(3) g/cm^3. The plates were rotated in opposite directions by a mechanical drive. Counter rotation of the plates to a given angle increases the thickness of the absorbing material in a smooth way and cancels, to first order, the effect of the small angular divergence of the beam. The correspondence between the computer set value of the degrader angle, and the actual angle was checked by observing the drive axis outside of the degrader chamber. The conservative uncertainty in the degrader angle was estimated to be less than 0.5 degree. The beam passed through a beryllium window into the gas cell filled with helium. The thickness of the window and it's diameter were 1.50 mm and 5.31 cm correspondingly. The window thickness nonuniformity was found to be less than 0.01 mm. The thickness and diameter of the beryllium window were chosen so that deflection under the load from the helium gas would not cause a significant change in thickness across its diameter. The material of the window contained less than 0.2% of heavier metallic contaminants according to the manufacturer (Bush-Wellman). A stack of four detectors of 300 mm^2 active area and 0.1, 0.5, 1.5 and 0.5 mm thick respectively was mounted on a central post inside the gas cell and was used for detection and identification of particles. The post could be moved to change the distance that beam traveled in the gas before reaching the stack. The gas pressure was measured with a capacitance manometer attached to the gas cell. The detector energy resolution was checked with ^{228}Th α-source and was found to be approximately 90 keV. The linearity of electronic channels was checked with a pulser. The trigger of the data acquisition was formed by signals from constant fraction discriminators (CFD). The CFD thresholds determined low-energy cutoff in the spectra (8-20 MeV, depending on detector). A large Si pin-detector (50mm×50mm×0.5mm) can be introduced in the beam upstream from the gas cell to monitor the beam intensity. The energy signals were recorded on an event-by-event basis and energy histograms were obtained in off-line analysis.

III. EXPERIMENT AND RESULTS

Fully-stripped primary ^{36}Ar and ^{40}Ar beams, at energies of 150.85 MeV/amu and 100.4 MeV/amu respectively, were delivered from the coupled K500 and K1200 cyclotrons to the gas cell. The initial spread in the beam momentum distribution was estimated to be 0.07(1)% by measuring the size of the beam spot in the dispersive image of the A1900 fragment separator. The central momentum of the beams was known to approximately 1/2000 accuracy from the value of magnetic rigidity of the fragment separator. A small uncertainty, less than 0.1%, in determination the beam momentum is associated with possible deviation of ion's path from the central trajectory. The beam intensity was attenuated by a large factor 1-3 10^6 to insure safe performance of the Si detectors and small dead time effects in the data acquisition. The typical counting rate in the detector was about 200-300 particles per second and the time duration of each measurement was set equal to two minutes. The energy spectra were taken for different settings of various parameters such as the degrader angle, gas pressure and the Si telescope position in the gas cell. The utilization of a Si telescope rather than a single detector allowed determination of the flux of the lighter reaction products. The typical rate of the fragmentation reaction products arising from interactions of primary ions with material of the glass degrader and the beryllium window was found to be a few per cent of the intensity of the primary beam. The beam intensity was monitored during the tests duration every few minutes by introducing the Si pin-detector in the beam. All the experimental results presented below have been corrected for the contribution of the reaction products and for changes of the primary beam intensity during data taking. Energy spectra observed in the detectors without the degrader and with an evacuated gas cell consisted of sharp ΔE peaks. Comparison of positions of the ΔE peaks with predictions of the stopping power calculations (see below) yielded the energy calibration. The full width at half maxima of the ΔE peaks observed in the calibration measurement were in agreement with the stopping power calculation when the non-homogeneity of the beryllium window and the Si detectors were taken into account in the calculations. Additional calibration points were obtained by introducing a thin degrader or the Si-pin detector in the path of the beam.

A. 150.85 MeV/amu ^{36}Ar beam.

A first set of measurements was performed with a monoenergetic ^{36}Ar beam, $B\rho$=3.6732 T·m. The thickness of the glass degraders was (2×3.640 mm) for zero tilt angle. As the degrader thickness follows the cosine function with the rotation angle, the combination of the degrader plates was chosen to keep the tilting angles in a range less than 15 degrees, thus minimizing the effect of overall uncertainty in the degrader thickness. All tests with this beam were done for the Si-telescope placed in the gas cell at distance of 43(0.2) cm from the Be window. The counting rate was measured by integrating the number of primary particles in the spectra. Examples of the normalized counting rate as a function of the degrader angle at 820 Torr, 1200 Torr pressures and the evacuated chamber are presented in Fig 2a. The data taken for pressures settings of 250, 550 Torr are not shown to relieve the busy figure.

The vertical error bars are attributed to fluctuation of the beam intensity and the horizontal error bars are due to uncertainties in determination of the degrader angle. The drop of the counting rate with increasing degrader angle for the case of the evacuated chamber is due to the increasing fraction of ions that stopped in the beryllium window. The faster drop in the counting rate of transmitted ions in the other two cases is due to additional stopping of ions in 43 cm of helium. The experimental results were compared with three types of stopping power calculations based on the three different energy-loss models [9–11] that are implemented in the LISE code [12]. The results of the ATIMA stopping power code [11], that was developed at GSI for relativistic heavy-ions were found to be in the best agreement with the experimental data and will be used throughout (the results from the two other models are also in reasonable agreement with the experiment). The results of the ATIMA calculations for three cases are presented in Fig 2 by the dashed lines.

Stopping very energetic heavy-ions in a gas volume at the end of their range requires careful control and the exact knowledge of physical and geometrical properties of all materials along the path of the beam. For example, the results of the predictions are significantly closer to the experimental measurements when the measured density for the borosilicate glass is used rather than the value tabulated in the literature (2.58 g/cm^3). The exact knowledge of the beam momentum is also crucial for predictive power of the calculation. As it is seen from Fig 2b and 2c, a small change the beam momentum leads to a significant shift in the calculated dependence of the transmitted fraction as a function of the degrader angle and small variations in the spread of the initial momentum distribution results in a failure to reproduce the slope of the dependence. None the less, the calculations are in good agreement with the measured values. It is important to point out that none of many parameters were adjusted in the stopping power calculations shown in Fig 2a. For instance, a significantly better correspondence of the data and the calculations could have been obtained by a small (less than 0.1%) variation of the beam energy, but such a change would have been inconsistent with the measured magnetic rigidity in the A1900.

B. 100.4 MeV/amu ^{40}Ar beam.

A second set of measurements was performed with a monoenergetic ^{40}Ar beam, $B\rho$=3.2840 T$\cdot$ m. The overall thickness of degraders was 3.51 (1.49 + 2.02) mm for zero tilt angle. The dependence of the transmitted fraction on the degrader angle was measured for several gas pressures with the Si-telescope again placed 43(0.2) cm from the beryllium window. The experimental results are also in good agreement with ATIMA calculations (Fig 3) although, as in the case of the first experiment, better agreement can be obtained if the value the initial energy is reduced in the calculations by 0.06-0.07%. As it seen from the difference in the position of the calculated curves (or the experimental data), more than 80% of the primary ions are stopped before the detector at a pressure of 800 Torr.

Additional measurements of the dependence of the counting rate on position of the Si-telescope in the cell were performed with this beam. The degrader angle was set to 10.7 degrees so that only a small fraction of ions ($\approx$ 12 %) were stopped in the beryllium window. When the gas cell was evacuated, the counting rate was found to be constant as a function of position of the detector over whole the entire within the gas cell (diamonds, Fig 4a) which indicates that, even after passage of the degrader and the window, the beam has a small divergence over the measured range. As expected, when the gas was introduced into the cell the transmitted fraction drops drastically with distance to the detector. The dependence of the transmitted fraction on distance to the detector is shown in Fig 4a for 800 Torr and 1500 Torr along with the ATIMA predictions for two degrader angles of 10.7 and 10.2 degrees. It can be seen from Fig. 4a that it was not possible perfectly to reproduce the dependence using the degrader angle of 10.7 degrees as the input value for the calculations; however, variation of the angle within a small range helps to obtain better correspondence. The best result is achieved when the angle in the calculations is taken to be 10.5 degrees. The experimental data taken for another degrader angle of 8.9 degrees and 1500 Torr gas pressure are reproduced well by the calculations (Fig. 4b).

During the measurements described above all of the transmitted primary ions are stopped in the first, 100 μm, detector of the stack. The spectra measured in the detector, after subtraction of a small contribution from reaction products that penetrate into the second detector, reflect the residual energy distributions of the primary ions that passed through the glass, beryllium and gas. A spectrum for the degrader angle of 10.7 degrees, 1500 Torr gas pressure and the detector position at 20 cm from the window is shown in Fig. 5a. There are two components in the spectrum, the low-energy component is associated with ions that have an energy below the maximum of the dE/dx stopping power curve (25 MeV) and the higher energy component is associated with ions above the maximum. It is interesting to observe the evolution of the energy spectrum with the distance that ions pass in the gas when all other conditions are kept the same : while the total number of counts drops due to stopping in helium, the relative contribution of the low-energy component gradually increases. It is also interesting to note that the low-energy component is less prominent when the gas cell is evacuated (Fig 5b). Several spectra taken with the gas cell filled with nitrogen or argon also exhibited the prominent low-energy component. The main features of the energy spectra are reproduced by the stopping power calculations (solid lines in Fig 5a,b).

IV. DISCUSSION

The results of the present measurements show that the majority of ions of primary beams can be successfully stopped in gas and that the stopping power calculations are in good agreement with data for argon ions. Small discrepancies between the calculations and experimental data could be due to uncertainties in the experimental parameters such as the degrader angle and initial beam momentum and momentum distribution. One may expect somewhat larger disagreement for the case of heavier elements (Z $\geq$ 25-30) where the reported experimental stopping powers in gases were found to be systematicaly smaller compared to solid materials [13,14]. However, for lighter elements this gas-solid effect is almost negligible [14]. A larger than calculated energy straggling may also be expected for heavier ions slowing down in diluted gas medium due to charge-exchange fluctuations.

The good agreement of the calculations with the measured results allows us to analyze the efficiency with which fast ions can be stopped and ultimately collected. The calculated fraction of 100 MeV/amu ^{40}Ar ions with momentum spread of 0.07% stopped in the Be window, in 50 cm of gas at 1 and 1.5 Bar and in the rear wall of the gas-cell are shown as a function of the degrader angle in Fig 6a . When the degrader angle is larger then a certain value the largest fraction stops in the beryllium window. This determines the working angle range for the degrader. An increased pressure in the gas cell reduces the distance needed to stop the ions and, in a cell with a finite length, and increases the number of ions stopped in the cell. For 1.5 Bar pressure and the degrader angle of 10 degrees 95% of the ions can be stopped in the gas. The situation changes when the ions have a larger distribution of initial momentum. The stopped fractions are shown for ΔP/P=0.2% in Fig 6b. A small increase in the initial spread of the momentum distribution is "amplified" after energy degradation leading to shallower dependence of the fraction stopped in the beryllium window. Even for small degrader angles some fraction of the ions stop in the window. On the another hand, for any degrader angle a significant fraction of ions passes through 50 cm of gas and stops in the rear wall of the gas cell. Both effects strongly reduce the stopping efficiency. Examining figures 6a and 6b one concludes that the stopping efficiency for secondary particles will be much lower since their momentum distribution is of order of a few percent. A bigger gas cell is required in this case without energy compression to obtain a significant collection efficiency of the ions that leave the entrance window. The minimum gas cell size filled with helium at 1 Bar that can stop one-half of an ^{40}Ar beam at different energies and momentum spreads is shown in Fig 7. The calculations are done for the same Be window and the degrader material as in the present study and the thickness of the degrader was optimized for each case. Note that the required size of the gas cell increases dramatically with beam energy and momentum spread.

It was suggested in [8] that the combination of homogeneous degrader following by a dispersive spectrometer and a wedge-shaped mono-energetic degrader placed at the dispersive plane can reduce the momentum spread of reaction products to the level of 0.2%. Taking as an example a case presented for RIA [15] with an initial beam energy of 400 MeV/amu and assuming degradation to 100 MeV/amu energy with the technique described in [8] results in a momentum spread of 0.2 %, one estimates that 75 % of the ions will be stopped in a 1 meter gas cell filled with helium at 1 Bar pressure (the estimation was done for ^{40}Ar beam assuming the same beryllium window and the 3.5 mm thick glass degrader). Therefore the stopping efficiency of ions from the RIA facility will be high in a large high pressure gas cell but the rapid collection of these ions remains a challenge.

V. ACKNOWLEDGEMENTS

We would like to thank Mr. J. Ottarson for his help with design and fabrication of the experimental setup, the staff the NSCL laboratory for their help during the experiments. We would like express our gratitude to Dr. O. Tarasov for his help in running the stopping power calculations with the LISE code. This work is support by the National Science Foundation grant PHY-01-10523 and by the US Department of Energy grant 00ER41144.

FIGURES

FIG. 1. General schematic view of the experimental setup.

FIG. 2. a. The normalized transmitted fraction of primary ions as a function of the energy degrader angle/thickness. The data are taken for 150.85 MeV/amu ^{36}Ar beam, for 810 Torr, 1200 Torr gas pressures and for the evacuated gas cell. The dashed lines represent ATIMA calculations. b. The comparison of 150.85 MeV/amu ^{36}Ar data taken for evacuated chamber with ATIMA calculations performed for three values of the beam energies 150.85 MeV/amu, 151.05 MeV/amu and 150.55 MeV/amu (spread of momentum is kept 0.07%) c. The comparison the same data with calculations performed for three three values of spread in the initial momentum distribution 0.03%, 0.07% and 0.15% (the beam energy is kept 150.85 MeV/amu)

FIG. 3. The normalized transmitted fraction of 100.4 MeV/amu ^{40}Ar ions as a function of the energy degrader angle/thickness. The data are taken for 810 Torr pressure and for the evacuated gas cell. The dashed lines represent ATIMA calculations.

FIG. 4. a. The dependence of the counting rate on the detector position within the gas cell measured for 800 Torr and 1500 Torr pressures and the evacuated gas cell. The data are taken for the degrader angle of 10.7 degrees. The ATIMA calculations are presented for two values of the degrader angle, 10.7 and 10.2 degrees. b. The data and calculations for the degrader at 8.9 degrees and 1500 Torr pressure.

FIG. 5. The energy spectrum taken for the detector position at 20 cm from the Be window at 1500 Torr and the degrader angle of 10.7 degrees (a) is compared with a spectrum taken for the evacuated gas cell and the degrader angle 12 degrees (b). The latter spectrum was collected for a longer time of six minutes. The corresponding spectra calculated with ATIMA are also shown.

FIG. 6. a. The calculated of stopping fraction in the beryllium window, 50 cm of helium gas at 1 bar (solid lines) and 1.5 bar (dashed lines) pressures, and the rear wall of the gas-cell as a function of the 3.5 mm degrader angle for ^{40}Ar at 100 MeV/amu beam and $\Delta P/P=0.07\%$, b. The similar calculations for $\Delta P/P=0.2\%$.

FIG. 7. The size of a gas cell required to stop half of ions as a function of the beam energy and momentum spread. The calculations are done for ^{40}Ar beam, the Be window and borosilicate glass degrader. The degrader thickness is optimize for each energy and momentum spread.

REFERENCES

[1] B. Jonson, Nucl. Phys. A **701** (2002) 35c and H.A. Grunder, Nucl. Phys. A **701** (2002) 43c.

[2] J. Äystö, Nucl. Phys. **A 693** (2001) 477 and references therin.

[3] G. Marx *et al.*, Hyp. Int. **132** (2001) 463.

[4] G. Savard, J. Schwartz, J. Caggiano, J.P. Greene, A. Heinz, M. Maier, D. Seweryniak, B.J. Zabransky, Nucl. Phys. A **701** (2002) 292c

[5] M. Wada *et al.*, Non-neutral plasma physics IV, AIP conference proceedings 606, San-Diego (2001) 625.

[6] T. Baumann *et al.*, Nucl. Phys. A **701** (2002) 282c.

[7] S. Schwartz *et al.*, Nucl. Instr. and Meth., in press (2002).

[8] H. Geissel, C. Scheidenberger, Proceedings of International NUPECC Meeting, GSI, December 1998, and H. Weick *et al.*, Nucl. Instr. and Meth. **B 164-165** (2000) 168.

[9] F. Hubert, R. Bimbot and H. Gauvin, ADND Tables **46** (1990) 1.

[10] J.F. Ziegler, J.P. Biersack and U. Littmark, Pergamon Press (1985).

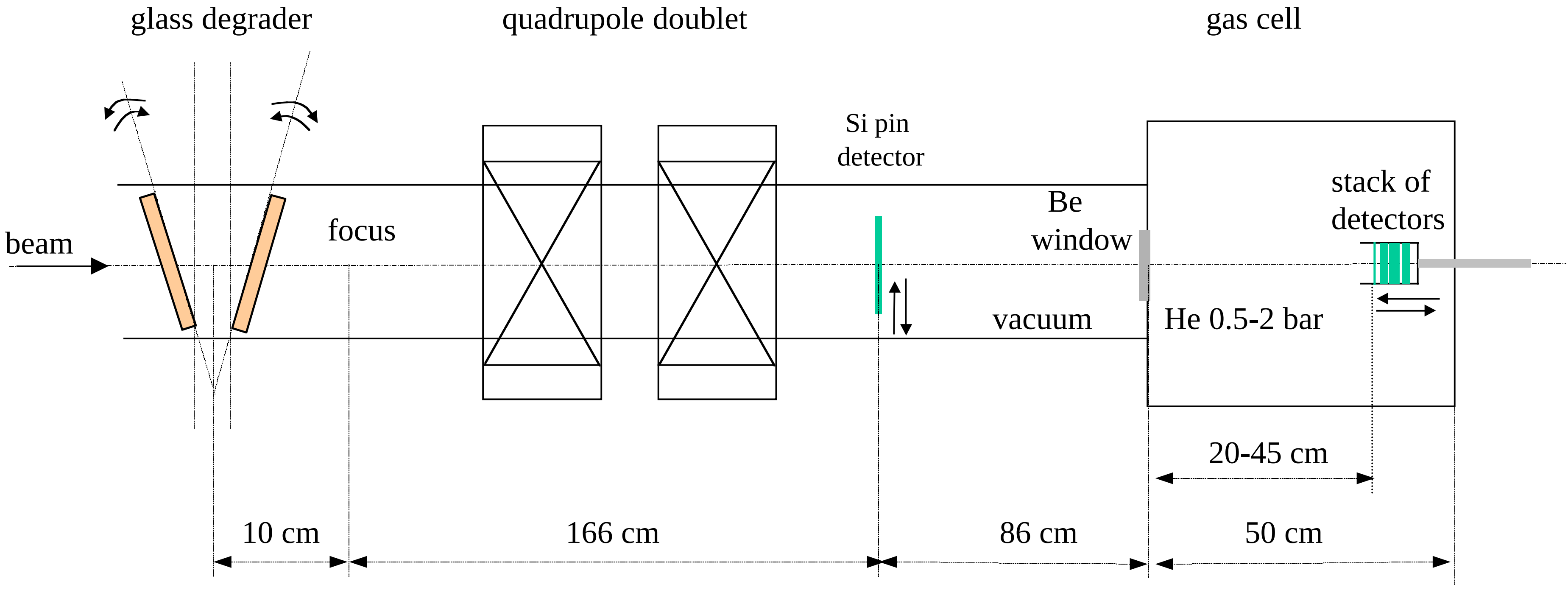
[11] http://www-aix.gsi.de/˜scheid/ATIMA1.html and C. Scheidenberger and H. Geissel, Nucl. Instr. and Meth. **B135** (1998) 25.

[12] O. Tarasov, D. Basin, M. Lewitowicz, O. Sorlin, Nucl. Phys. A **701** (2002) 661c.

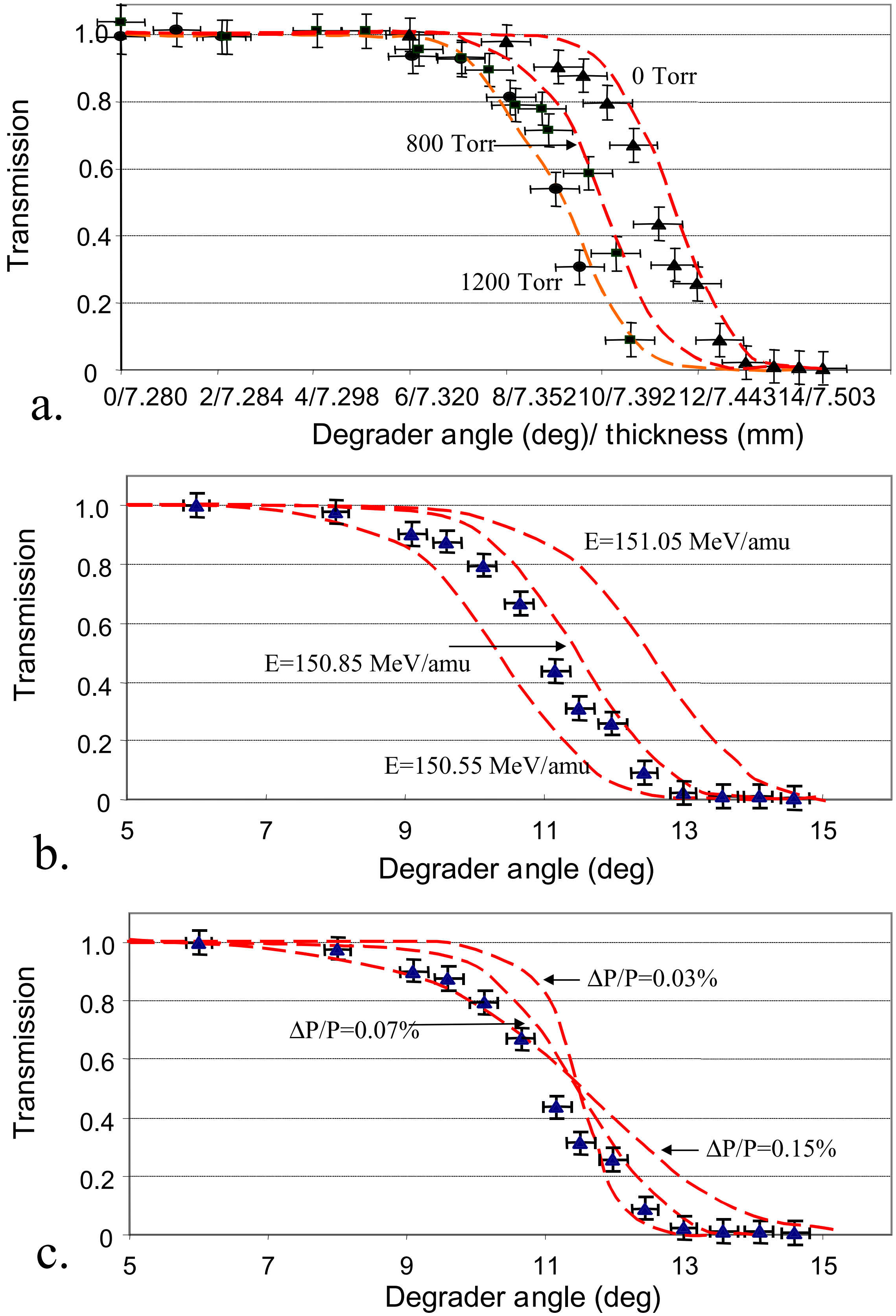
[13] H. Geissel, Y. Laichter, W.F.W. Scneider and P. Armbruster, Phys. Lett. **A88** (1981) 26.

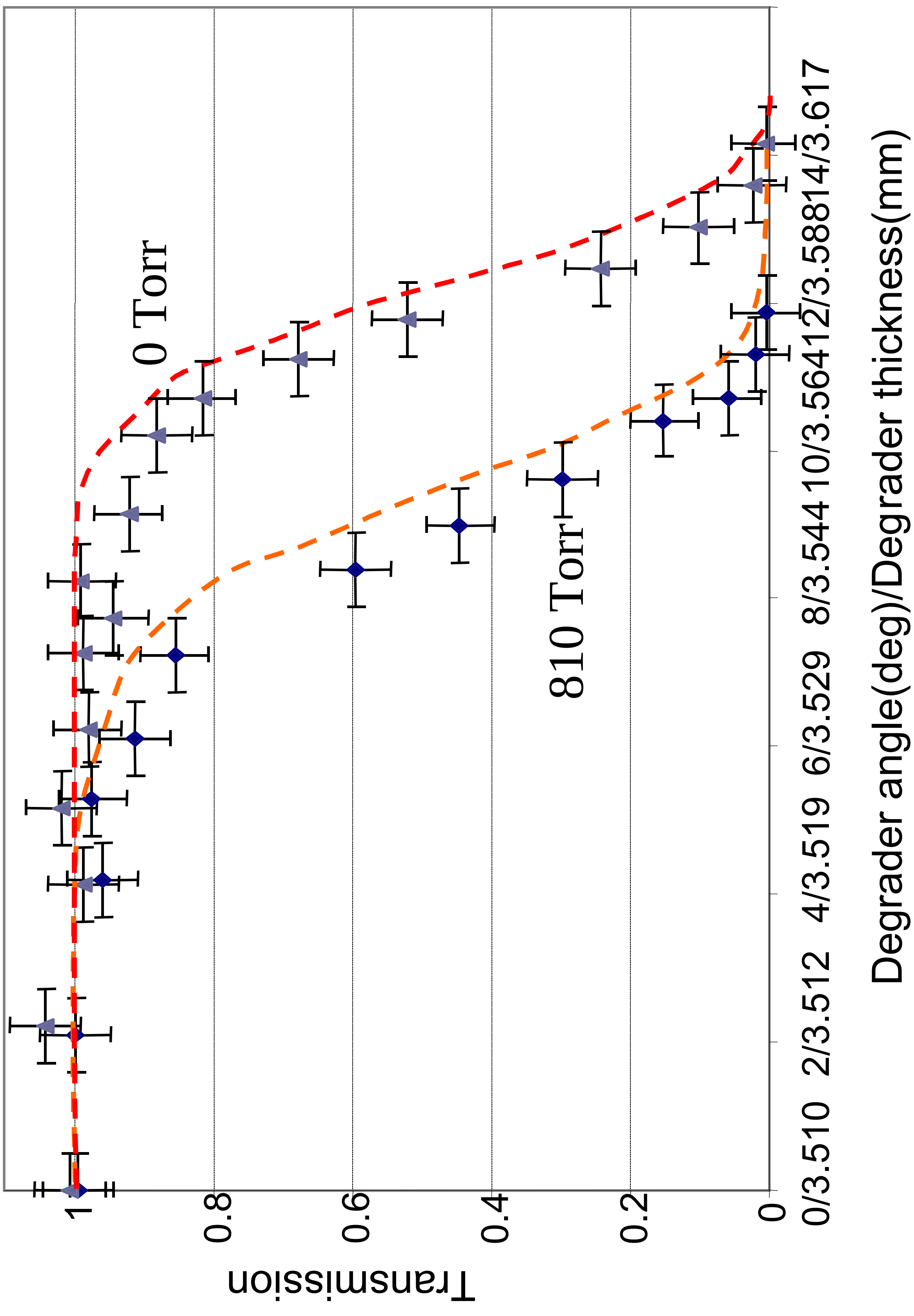
[14] R. Bimbot, C. Cabot, D. Gardes, H. Gauvin, I. Orliange, L. De Reilhac and K. Subotic, Nucl. Instr. and Meth. **44** (1989) 19-34.

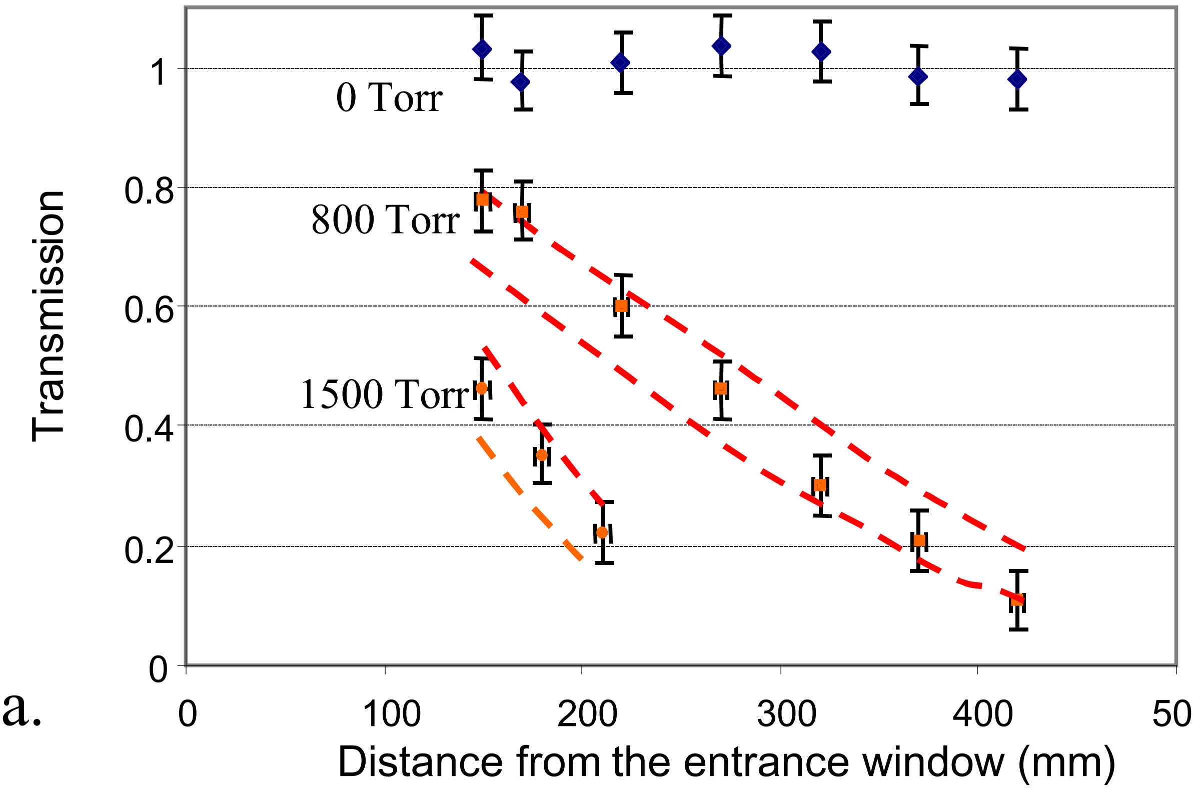
[15] http://www.phy.anl.gov/ria


glass degrader
quadrupole doublet
gas cell
beam
focus
Si pin
detector
Be
window
vacuum
stack of
detectors
He 0.5-2 bar
20-45 cm
10 cm
166 cm
86 cm
50 cm

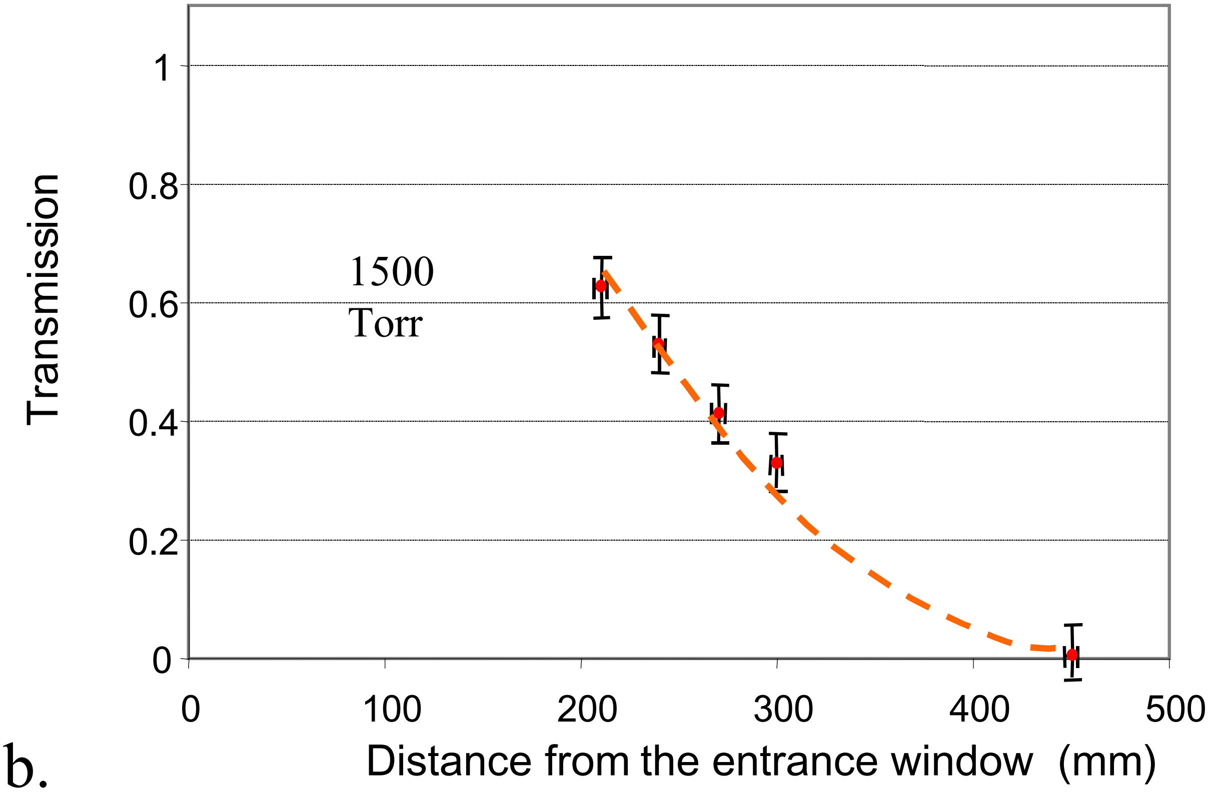
A


a.
Transmission
1.0
0.8
0.6
0.4
0.2
0
0 Torr
800 Torr
1200 Torr
0/7.280
2/7.284
4/7.298
6/7.320
8/7.352
10/7.392
12/7.443
14/7.503
Degrader angle (deg)/ thickness (mm)
b.
Transmission
1.0
0.8
0.6
0.4
0.2
0
E=151.05 MeV/amu
E=150.85 MeV/amu
E=150.55 MeV/amu
5
7
9
11
13
15
Degrader angle (deg)
c.
Transmission
1.0
0.8
0.6
0.4
0.2
0
ΔP/P=0.03%
ΔP/P=0.07%
ΔP/P=0.15%
5
7
9
11
13
15
Degrader angle (deg)

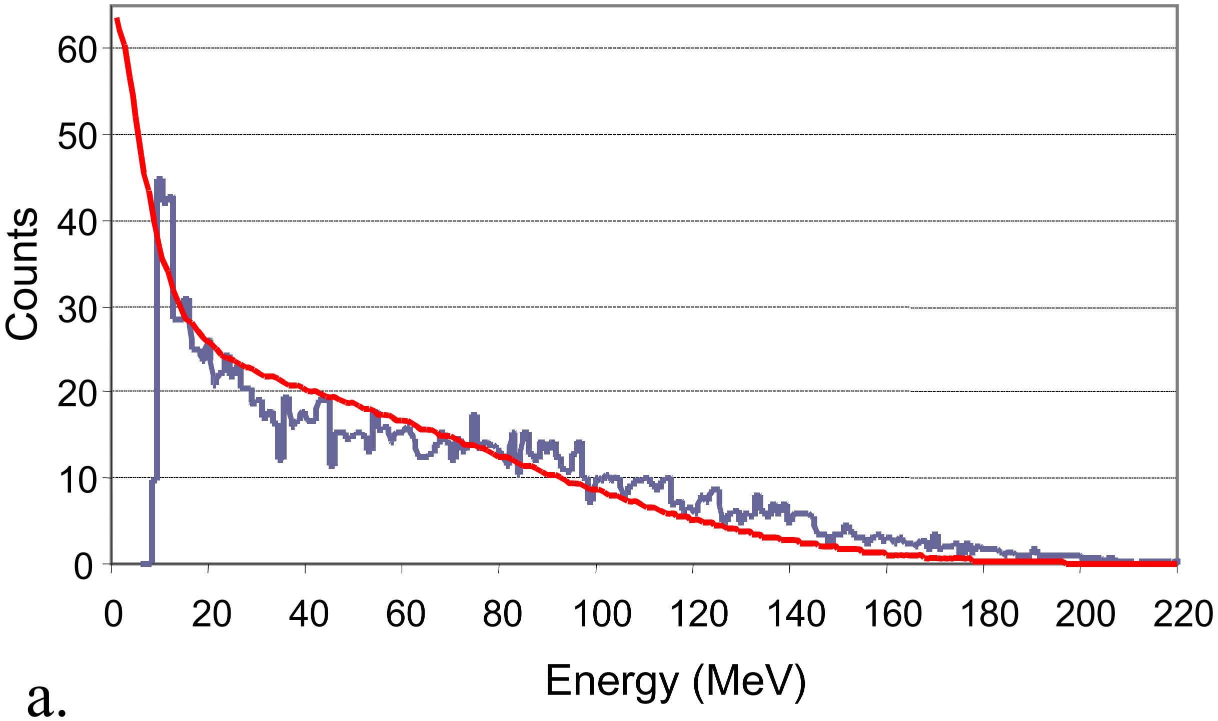

Transmission
0
0.2
0.4
0.6
0.8
1
0/3.510
2/3.512
4/3.519
6/3.529
8/3.544
10/3.564
12/3.588
14/3.617
Degrader angle(deg)/Degrader thickness(mm)
0 Torr
810 Torr


Transmission
1
0.8
0.6
0.4
0.2
0
0 Torr
800 Torr
1500 Torr
0
100
200
300
400
500
Distance from the entrance window (mm)

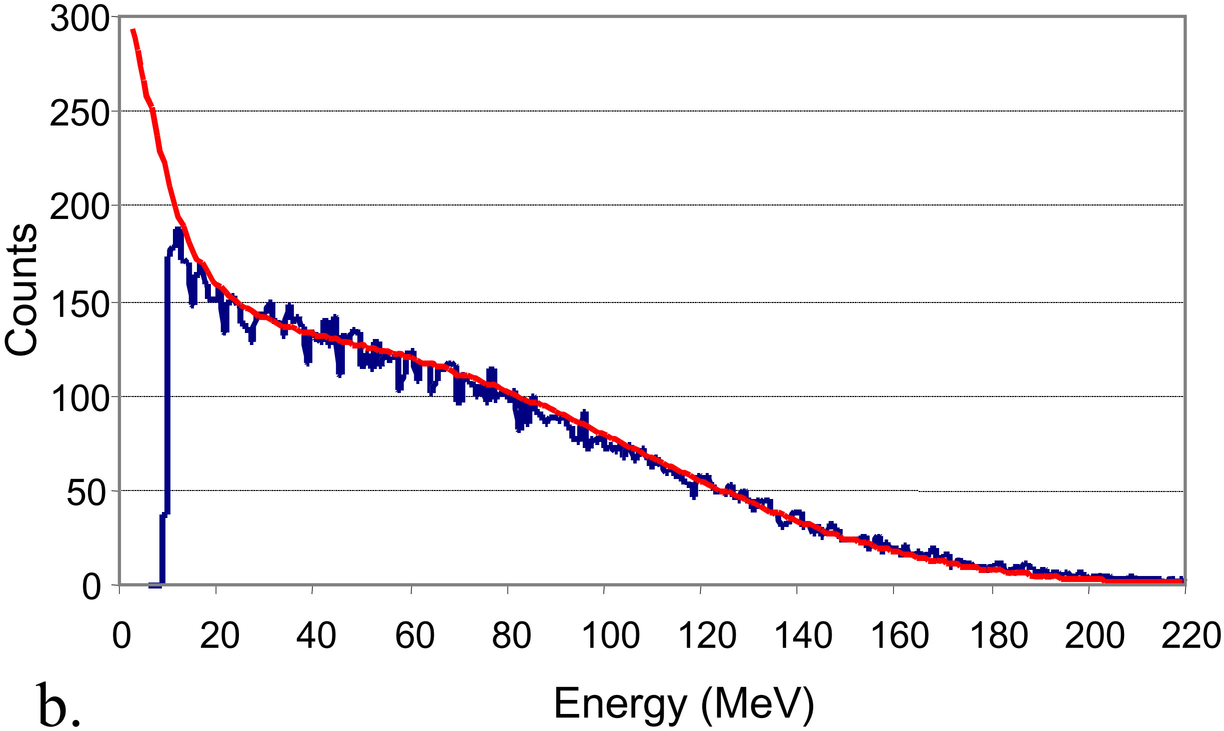
a.


Transmission
1
0.8
0.6
0.4
0.2
0
1500
Torr
0
100
200
300
400
500
Distance from the entrance window (mm)

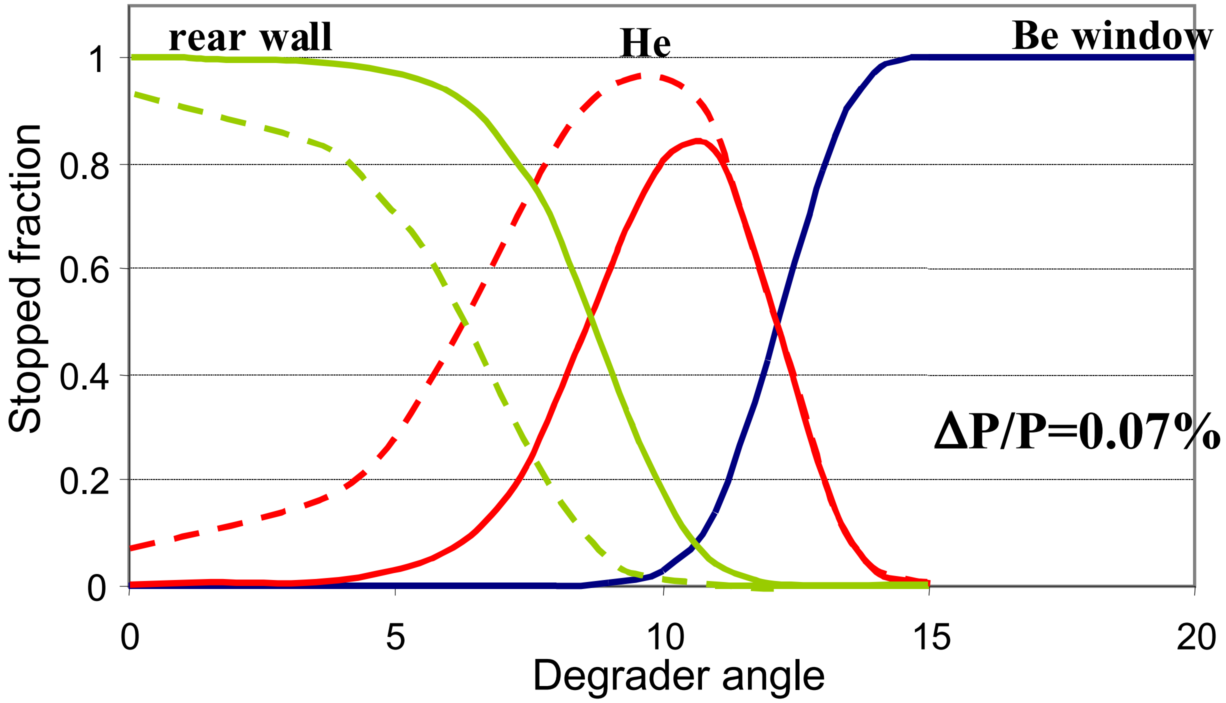
b.


Counts
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140
160
180
200
220
Energy (MeV)

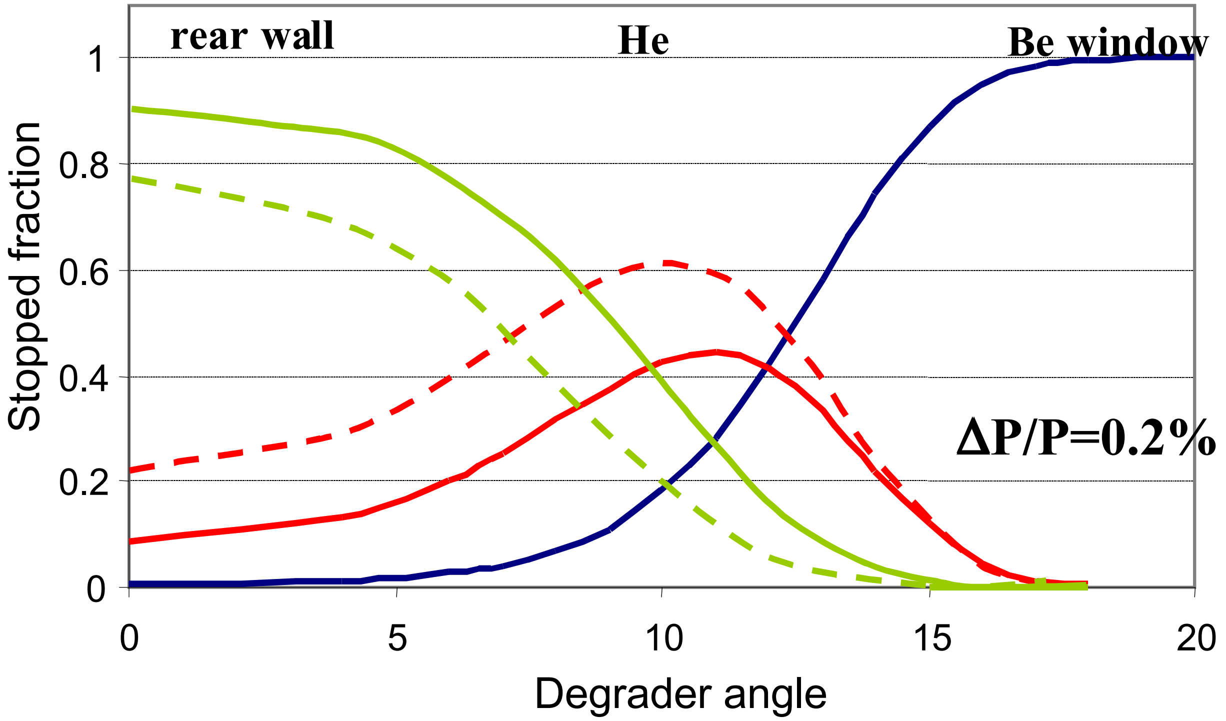
a.


Counts
0
50
100
150
200
250
300
0
20
40
60
80
100
120
140
160
180
200
220
Energy (MeV)

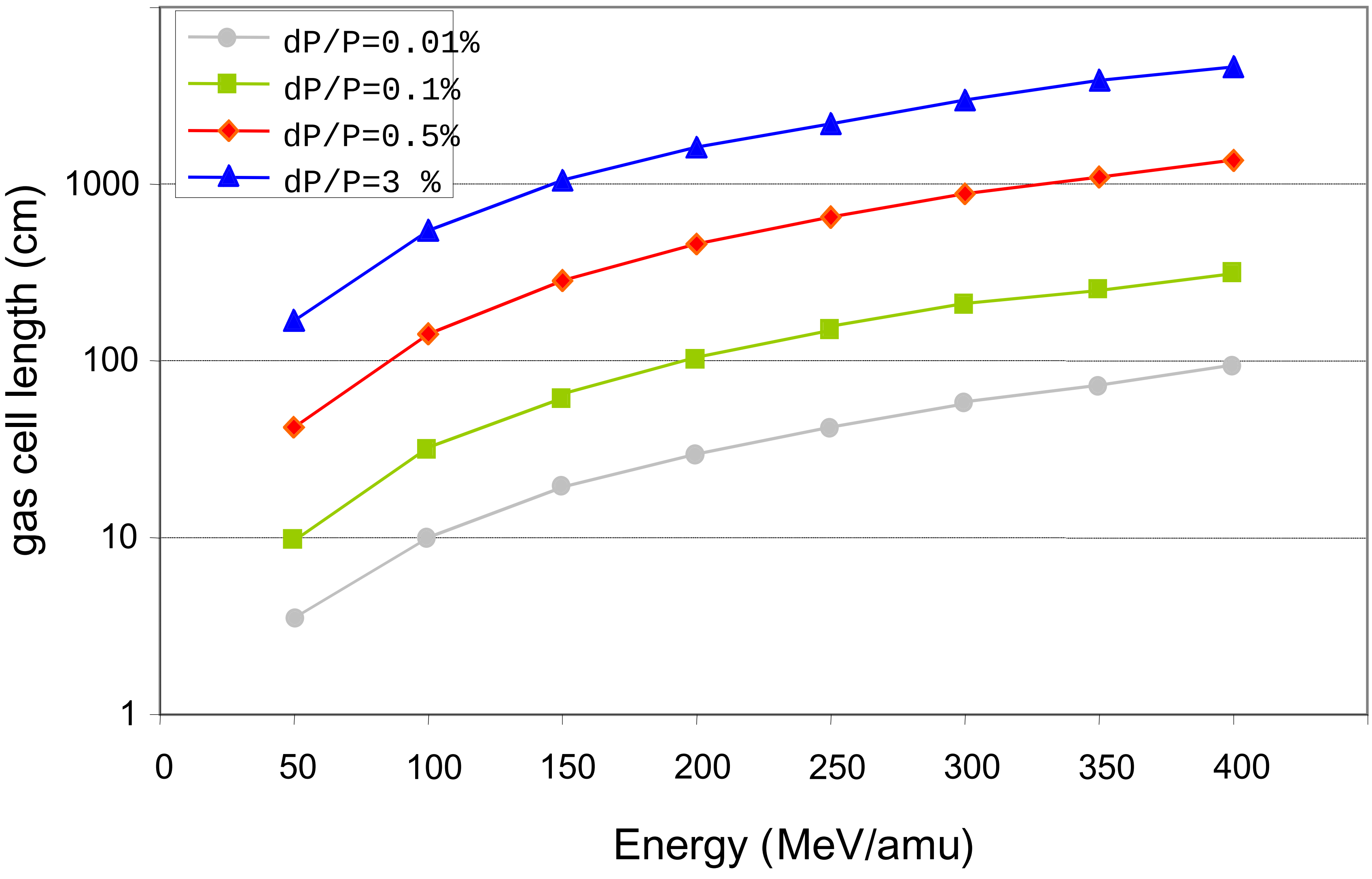
b.


rear wall
He
Be window
ΔP/P=0.07%
Stopped fraction
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
Degrader angle

a.


rear wall
He
Be window
ΔP/P=0.2%
Stopped fraction
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
Degrader angle

b.


dP/P=0.01%
dP/P=0.1%
dP/P=0.5%
dP/P=3 %
gas cell length (cm)
1000
100
10
1
0
50
100
150
200
250
300
350
400
Energy (MeV/amu)