Catching energetic heavy-ion beams in gas

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Abstract

The stopping of argon beams at energies up to 100 MeV/u in a combination of an aluminum energy degrader and a helium gas cell was investigated. The transmission of ions through the gas was measured at different gas pressures. A Monte Carlo simulation was applied in order to calculate the spatial distribution of ions stopped in the gas. It was found that the width of the range distribution was not largely enhanced by the aluminum energy degrader.

Key words: radioactive beams, energy loss, range straggling
PACS: 24.10.Lx, 34.50.Bw

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1 Introduction

The study of nuclei far from stability is closely linked to the ability to produce them with intensities and at energies that are matched to the experimental technique that is being employed. Although a large variety of rare isotopes can be produced with high intensities at ISOL (isotope separator on-line) facilities, chemical limitations exclude some elements, and the efficient extraction of isotopes with very short half-lives can be problematic. Projectile fragmentation and in-flight separation techniques, on the other hand, are able to separate sub-microsecond isotopes by physical methods, without any limitations to certain elements. However, the efficient production and in-flight separation involves high beam energies of at least 50–100 MeV/u. This makes the study of very

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Preprint submitted to Nuclear Instruments and Methods B *18 July 2001*

exotic and short-lived nuclei at low energies, as for example needed for ion traps or laser spectroscopy, difficult or even impossible.

Particles with energies of a few MeV/u can be stopped in a catcher gas cell. From the gas cell, the ions can then subsequently be extracted in a very short time of less than a millisecond, as is done in the IGISOL (ion guide isotope separator) technique [1], and reaccelerated to modest energies of typically a few tens of keV. For fast fragmentation beams with energies of 50–100 MeV/u, however, the length of such a cell would be prohibitively large. A solution would be to produce and separate the exotic nuclei at high energies and slow them down far enough to be able to stop them in a catcher gas cell of manageable dimensions. The goal is to minimize the size of the gas cell required to stop the majority of the exotic nuclei that entered the cell.

The atomic slowing down in matter provides the fastest method to reduce an energetic beam to energies which are suited to catch the ions in a gas cell. The efficiency of the gas stopping technique will depend on how energy straggling in the degrader and stopping gas affects the range distribution of the ions. To investigate this issue, we undertook a simple experiment at the National Superconducting Cyclotron Laboratory and measured the range straggling of ^{36}Ar ions in a He-filled gas cell after they passed through an aluminum energy degrader. A Monte Carlo simulation was employed to reproduce these measurements.

2 The measurement

Primary beams of ^{36}Ar at 75 and 100 MeV/u were delivered from the K1200 cyclotron. Figure 1 shows a cross sectional view of the experimental setup. The heavy-ion beams passed through a Zr vacuum window of 21.6 µm thickness, a 174 µm plastic scintillator, and a variable Al energy degrader. The energy degrader could be tilted in order to adjust its effective thickness. Before the beams entered the He-filled gas cell through a 127 µm kapton window, they also passed through about 120 mm air in total. Two 500 µm silicon detectors

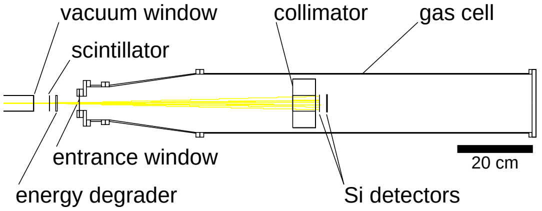

Fig. 1. Cross sectional view of the experimental setup.

measuring 5 cm by 5 cm were mounted behind a steel collimator with an opening of 4 cm by 4 cm. The purpose of the collimator was to shield the detectors from particles that possibly were scattered off the gas cell walls. The collimator and the detectors were placed on a rail and could be positioned at various distances from the entrance window of the gas cell.

The combined effect of energy straggling in the degrader and range straggling in the gas was determined indirectly by the measurement of transmission as a function of gas pressure. The transmission of primary beam particles between the plastic scintillator and the set of silicon detectors inside the gas volume was measured at pressures from 0 to 130 kPa. The thickness of the aluminum degrader was adjusted so that the complete range distribution, i.e. from maximum transmission at zero gas pressure to no transmission at maximum gas pressure, could be sampled. Reaction products were discriminated by a ΔE-E measurement in the silicon detectors. In order to be identified, the particles had to be detected in both silicon detectors. Therefore, particles that stopped in the first silicon detector were not counted. The equivalent range distribu-

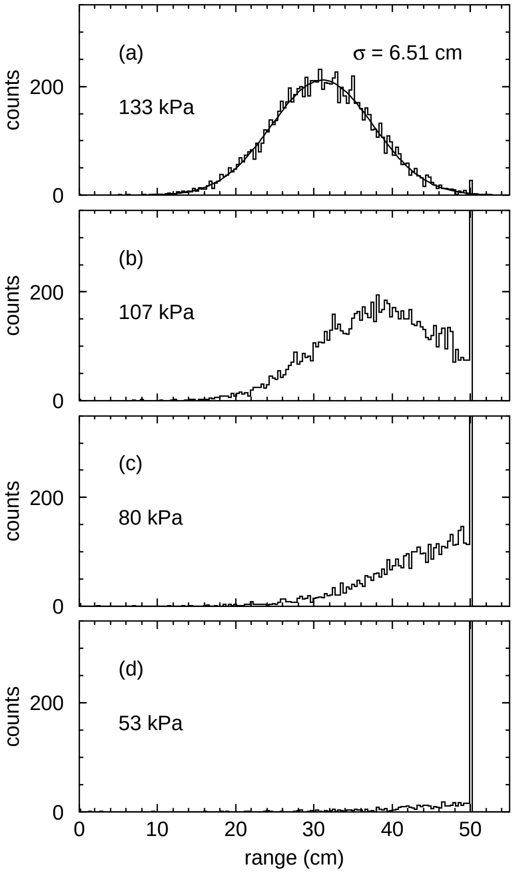

Fig. 2. Simulated range distributions of ^{36}Ar ions at 100 MeV/u, entering a 50 cm deep gas volume through a 4.135 mm Al energy degrader. Resulting distributions for different gas pressures are displayed (a–d).

tion that would have been obtained had all particles stopped in the gas was subsequently determined using a simulation that reproduced the transmission measurements.

Figure 2 shows how range distribution and the transmission curve are related using the results of a simulation with an idealized setup. In this simulation, a 100 MeV/u ^{36}Ar beam enters a He gas volume of 50 cm length through a 4.135 mm Al energy degrader. At 133 kPa gas pressure, almost all ions are stopped in the gas. The simulated range distribution has a sigma of 6.51 cm, corresponding to 15.3 cm FWHM. With decreasing gas pressure, more ions are transmitted to the end of the gas volume, finally yielding the complete experimental transmission curve. The range distribution widens as the stopping gas becomes thinner, therefore the simulation is used in the analysis to associate the measured transmission curve with a range distribution at a single gas pressure.

3 The simulation

The geometry of the gas catcher cell has a major impact on the ratio of ions that can be stopped in the gas volume of the cell. If the stopped ions are to be extracted from the gas cell, it is crucial to know where the ions stop in order to make precise predictions about the extraction efficiency and lifetime limitations.

Considering this, we chose the Monte Carlo code GEANT [2,3] in combination with the hadronic interaction package FLUKA [4,5] for our simulation. With this code, the complete geometry of the gas cell could be entered into the simulation. This is illustrated in Fig. 3, where the simulated position of stopped Ar-ions is plotted. An overlaid plot of the setup shows the corresponding location of the stopped ions.

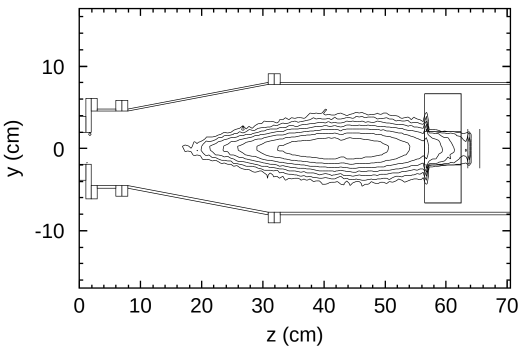

Fig. 3. Simulated range distribution of 100 MeV/u ^{36}Ar ions in 133 kPa He gas for the complete experimental setup.

Careful checks and adjustments of parameters were undertaken in order to achieve correct results from the GEANT simulation. One of these checks is the comparison with other energy-loss programs. We compared simulations of SRIM [6] and GEANT for the transmission of 100 MeV/u ^{36}Ar passing through a 4.135 mm Al energy degrader directly into 50 cm of He gas. The results of the two simulations are plotted in Fig. 4. Both distributions were fitted with a Woods-Saxon curve yielding width parameters of 10.0 kPa for the SRIM simulation (dashed curve) and 10.4 kPa for the GEANT calculation (solid curve), which is a good agreement. The GEANT simulation gives us the possibility to track each ion through various materials and the gas, taking the detailed geometrical setup into account.

The measured transmission curves for ^{36}Ar at 100 and 75 MeV/u are presented in Fig. 5. For the measurement at 100 MeV/u, the detectors were placed at 63.5 cm behind the entrance window of the gas cell. The energy degrader was adjusted to a thickness of 3.53 ± 0.10 mm. In case of the 75 MeV/u measurement, the distance from the entrance window to the detectors was 63.2 cm, and a 1.75 ± 0.10 mm degrader was used.

Three parameters in the simulation were adjusted in order to reproduce the measured curves: the thickness of the aluminum degrader, the divergence of the beam, and the energy spread of the incoming beam particles. By changing the energy degrader thickness, the complete transmission curve could be moved to higher or lower pressure values, i.e. it could be shifted along the pressure scale. Degrader thicknesses of 3.42 mm (100 MeV/u simulation) and 1.78 mm (75 MeV/u simulation) that were needed in order to match the experimental transmission curves are comparable to the experimental degrader thicknesses. Since there were no position sensitive detectors used in the experimental setup, the transmission at zero gas pressure was used to adjust the angular divergence of the incoming beam for the simulation. Finally, inhomogeneities in the degrader thickness and the energy spread of the incoming beam particles

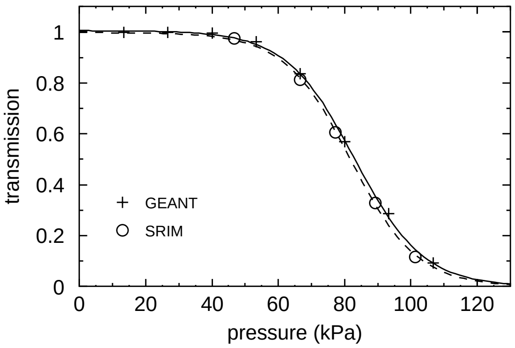

Fig. 4. Comparison of transmission curves calculated by SRIM (circles) and GEANT (cross hairs). Fits through the GEANT (solid curve) and SRIM (dashed curve) data points show the good agreement between the two simulations.

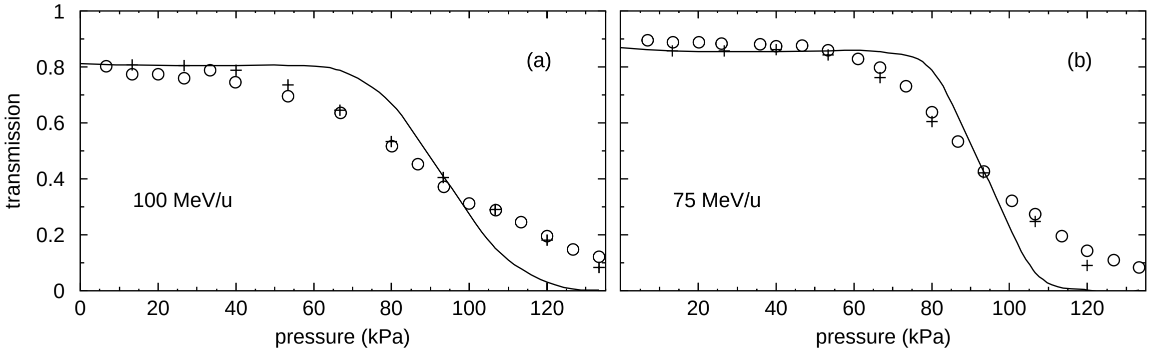

Fig. 5. Transmission curves obtained with beams of ^{36}Ar at 100 MeV/u (a) and 75 MeV/u (b). The experimental data (circles) are shown together with the results of the GEANT calculation (cross-hairs). The solid curves correspond to calculations with no energy spread in the primary beam.

broadened the range distribution in the gas cell. In the simulation, only the energy spread of the incoming beam was adjusted. The measured transmission curves could be reproduced with an energy spread of 3.5‰. The energy spread of the primary beam in the experiment of about 1‰ and the aluminum degrader's surface roughness of the order of 15 µm, taken together, agree with the energy spread used in the simulation. Transmission curves that were calculated using a mono-energetic beam, reflecting the actual range distribution of the stopped ions in the gas, are plotted as solid lines in Fig. 5.

In order to yield the width of the range distribution stopped in the gas after passing through just the energy degrader, we simulated an idealized setup consisting of an Al energy degrader directly followed by a large He gas volume. For this simulation, we used the same parameters with which we were able to reproduce our experimental data, except for the spread in beam energy.

The GEANT simulation yields a width of the range distribution for a 100 MeV/u ^{36}Ar beam on 4.135 mm Al and He gas at 101.3 kPa of $\sigma_{\mathrm{R}} = 8.5$ cm. Without the energy degrader or entrance window, the range straggling in the gas would be 7.6 cm according to GEANT. While the range straggling is comparable to what can be achieved using an additional energy degrader, the mean range increases to about 50 m! This is also in agreement with SRIM, which gives value of $\sigma_{\mathrm{R}} = 8.4$ cm at a mean range of about 50 m.

4 Conclusion

We found that energetic primary beams of heavy ions can be stopped in a combination of solid energy degrader and gas cell, while the range distribution is not considerably enlarged compared to the hypothetical case where just a gas cell is used to stop the particles. However, the comparison of measurement and simulation shows that the homogeneity of the energy degrader and the energy spread of the beam are crucial parameters in obtaining a narrow range distribution. The energy spread of the incoming beam particles directly influences the range distribution. For secondary beams with typically large energy spreads, special measures have to be taken in order to overcome this problem. If the main slowing down is done in a homogeneous degrader that is followed by a dispersive spectrometer stage, a wedge-shaped mono-energetic degrader at the dispersive plane can exactly compensate the energy spread of the secondary beam and the energy straggling that arises in the homogeneous degrader [7]. This method of “range bunching” results in a range distribution that is even narrower than what can be achieved with an ideal mono-energetic beam and a homogeneous energy degrader.

Major steps to realize the stopping and subsequent re-acceleration of energetic rare isotope beams are currently being undertaken at several laboratories throughout the world. While the task of catching a *slow* beam in a gas cell has been investigated for several years, experiments that study how to slow down a *fast* beam and retain a high beam quality are still at the beginning.

A gas cell that is able to stop secondary beams produced by fast fragmention is also planned to be employed at the Rare Isotope Accelerator (RIA), the proposed next-generation radioactive beam facility in North America [8, 9]. The range straggling investigated in this paper represents one of the crucial problems that need to be addressed in this context.

The authors would like to thank G. Bollen and D.J. Morrissey for helpful discussions. We acknowledge support by the U.S. National Science Foundation under grant PHY 95-28844.

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