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A study of the cyclotron gas-stopping concept for the production of rare isotope beams

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ABSTRACT

The proposed cyclotron gas-stopping scheme for the efficient thermalization of intense rare isotope beams is examined. Simulations expand on previous studies and expose many complications of such an apparatus arising from physical effects not accounted for properly in previous work. The previously proposed cyclotron gas-stopper geometry is found to have a near null efficiency, but extended simulations suggest that a device with a much larger pole gap could achieve a stopping efficiency approaching roughly 90% and at least a 10 times larger acceptance. However, some of the advantages that were incorrectly predicted in previous simulations for high intensity operation of this device are compromised.

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1. Introduction

The thermalization of energetic beams produced by fragmentation, in-flight fission or fusion-evaporation reactions is an important technology for the production of low-energy rare isotope beams. It can provide access to radioactive beams of refractory or reactive elements not amenable to the ISOL technique. These thermalizing techniques are currently being aggressively developed and are essential to the next generation of radioactive beam experiments. The production of such beams would allow reaccelerated beam experiments to venture into a regime of exotic isotopes beyond the reach of current target/ion source assemblies, allowing for a wealth of new experiments to be developed.

Thermalizing energetic ions in a gas volume and extracting them for post-acceleration is a difficult task, but one that has now been realized in many facilities interested in ISOL type experiments [1–4]. Such facilities typically cool beams through energy loss in high-purity helium, guide the thermalized ions to a nozzle where they are carried by gas flow through a differential pumping aperture after which the heavy ions are extracted and transported to a post-accelerator or used in experiments involving cooled rare isotopes. While this approach has been shown to work well at low intensity, most approaches have shown limitations with incident beam intensity many orders of magnitude lower than what is expected for next generation radioactive beam facilities [5,6]. The cyclotron stopper has been suggested as a way to overcome this limitation.

2. Proposed concept

The cyclotron stopper technique was proposed by Katayama et al. [7] and a detailed study by Bollen et al. [8] was recently published. This approach involves the use of a weakly focusing cyclotron magnet which provides ions an essentially unlimited path length due to cyclotron motion, allowing the use of gas pressures significantly lower than current techniques. As the reaction products ionize the helium gas they slow down and spiral in towards the center where they eventually reach thermal energies. The desired end effect is to concentrate cooled heavy ions near the center of the magnet, away from the bulk of the ionized helium.

The separation of cooled heavy ions from the majority of ionized gas allows for efficient extraction and removes several difficulties that have plagued most other gas catcher schemes. The undesirable bulk of helium ions can then be removed with the use of charge collection electrodes without affecting the cooled fragments. Near the center of the magnet, the thermalized heavy ions are carried towards an RFQ ion guide through the use of a DC electric field, an RF-carpet, and gas flow.

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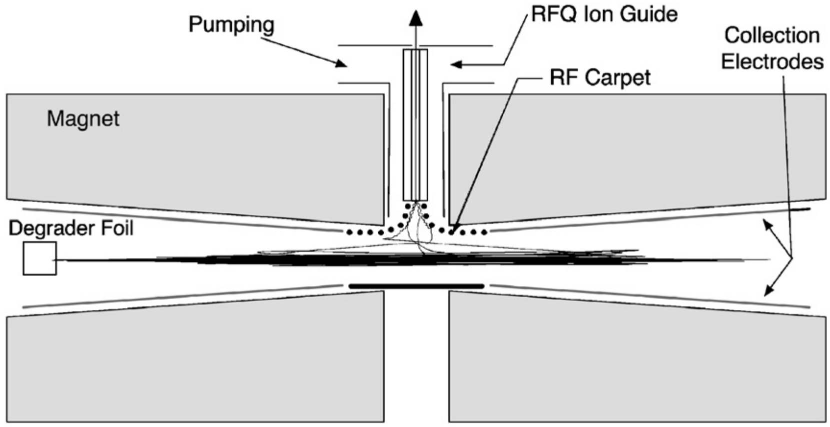

Fig. 1. Concept for the cyclotron gas-stopper studied in Ref. [8].

The main features that make such a concept attractive for use in stopping energetic ions are its extremely long stopping length, low gas pressure, and the clear separation between ionized helium and cooled heavy ions. A study of this concept was reported in Ref. [8] and has been used as a starting point for this study. Fig. 1 illustrates a rough layout for the concept proposed in Ref. [8]. Bollen et al. conclude that for a prototypical Bromine radioactive beam a stopping efficiency approaching 100% can be reached in such a device with a 4 cm gap between the charge collection electrodes. This result is surprising in that the lateral straggling of such a beam coming to rest in gas, in the absence of magnetic or electric fields, far exceeds this dimension.

We therefore repeated the simulations while including various effects that were either ignored or improperly treated in Ref. [8]. In addition, we also performed simulations for injection of beam with phase-space more representative of modern large acceptance spectrometers. For the geometry and beam properties used in Ref. [8], we find a stopping efficiency down by over two orders of magnitude compared to their results. Our simulations indicate that a pole gap up to 18 times larger is required to obtain sizable efficiencies. This not only increases the technical difficulties with the magnet but also removes some of the advantages that were proposed for operation at high intensity. By modifying the injection scheme we can, in addition, increase the acceptance of the device by roughly an order of magnitude.

The approach taken below was to first reproduce the results of Ref. [8], then systematically improve on this simulation by

- Correcting the charge-changing collision method used in that paper.
- Including proper charge state of ions in solids for beam exiting the degrader.
- Adding angular straggling.
- Performing simulations with larger phase-space for the incoming beam.
- Investigating alternative means of focusing.

The basis for the changes between the present simulations and the work of Ref. [8] is given when each change is made and conclusions are stated on the status of this approach as an alternative for high intensity operation for both the original and the new larger acceptance geometry proposed here.

3. Simulation

3.1. Basis for simulation

All of the simulation details discussed in this subsection, unless otherwise stated, have been taken directly from Ref. [8] and have been used as a starting point for simulations discussed later in this paper. Information and details beyond what are discussed here can be found in Ref. [8]. The simulations are performed using a Monte Carlo ray tracing code and consist of a weakly focusing cyclotron magnet, 1 m in radius, filled with 10 mbar helium gas at 0 °C. The peak magnetic field of the magnet is $B_0 = 2\,\mathrm{T}$ with a field index of $n_0 = 0.2$ and a radius of injection $r_{\mathrm{inj}} = 0.8\,\mathrm{m}$.

Bromine is used as a test case for the simulation because of its moderate mass and because of the charge-exchange data available for this element. The test beam consists of 100 MeV/u ^{78}Br passing through an aluminum degrader resulting in a beam with an average energy of 610 MeV. The initial simulation assumes that the beam exiting the degrader has an average energy spread $\Delta E/E$ of 20%, a beam half width of 5 mm and a beam half divergence of 10 mrad.

The motion is modeled for non-relativistic ions using an axially symmetric form $\vec{B}(\vec{\rho}, z) = B_\rho \cdot \hat{\rho} + B_z \cdot \hat{z}$, where, in a paraxial approximation, B_ρ and B_z are given by

$$B_\rho = -(n_0 \cdot B_0/r_{\mathrm{inj}})z \tag{1}$$

$$B_z = B_0 - (n_0 \cdot B_0/r_{\mathrm{inj}})\rho \tag{2}$$

Energy loss is modeled using stopping tables for bromine ions in helium provided by SRIM [9] for a range of energies from 1 GeV to 100 eV. Energy straggling is not considered since it corresponds to a deviation in the total path length of less than 5% and therefore does not have a sizable impact on the simulation. Angular straggling was also not considered in the original simulation because its effects were thought by Bollen et al. [8] to be small. Verifying this assumption was one of the leading motivations for trying to reproduce the simulations reported in Ref. [8]. As will be evident later, the effects due to angular straggling are not negligible.

Charge-exchange collisions of Br with helium are modeled for single-electron exchange. Multiple-electron loss and capture can be ignored since their cross-sections are in general orders of magnitudes smaller. The average charge state $\bar{q}$ as a function of ion velocity v is calculated according to semi-empirical formulae fitted to experimental data [10],

$$\bar{q}/Z = \frac{\lg(v/m_1 Z^{\alpha_1})}{\lg(n_1 Z^{\alpha_2})} \quad (0.3 \leqslant \bar{q}/Z \leqslant 0.9) \tag{3}$$

$$\bar{q}/Z = AvZ^{-1/2} \quad (\bar{q}/Z < 0.3) \tag{4}$$

where Z is the proton number and $m_1, n_1, \alpha_1, \alpha_2$, and A are parameters fitted to experimental data.

The cross-sections for charge loss σ_l and capture σ_c for a given charge state q are given by

$$\sigma_c = \frac{\sigma_0}{2} \cdot e^{a_c(q-\bar{q})} \tag{5}$$