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MEASUREMENT OF CHARGE EXCHANGE LOSSES IN THE VICKSI CYCLOTRON

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Summary

High-energy (E≈5 to 20 MeV/amu) ion-atom collisions have been studied using the internal ion beam of the VICKSI separated-sector heavy-ion cyclotron. Various combinations of accelerated ions and target gases have been investigated using the beam attenuation method to infer charge-exchange cross sections as a function of ion energy and atomic target. The analysis indicates $\sigma_{\Delta q} \approx \sigma_q \beta^{-1}$ (where β=v/c) for Z_{ion}=6, 20 and 40 and E_{ion}=0.5 to 20 MeV/amu in N_2, Ar and Kr gas.

Introduction

The energy- and ion-dependence of charge exchange cross sections at high velocities (E>5 MeV/amu) is largely unknown.[1] Such information is needed in the design of future heavy-ion accelerators and storage rings for nuclear research and fusion.[2] Also, high-energy charge-exchange collisions are important in astrophysical processes[3] and quantitative data would be useful. A program to study these collisions has been initiated at the VICKSI heavy ion cyclotron and preliminary data have been reported.[4]

Experimental Method

The VICKSI accelerator consists of a single-ended 6 MV Van de Graaff positive-ion injector and a large separated-sector isochronous cyclotron (E_{max}=130 q^2/A). The beams from the injector are stripped to a selected charge state, q, with a carbon foil or N_2 gas, and then injected ($R_i \approx 0.4$ m) and accelerated to extraction radius ($R_f \approx 1.7$ m) in separated orbits (N≥100 turns). The energy separation between turns is $\Delta E \propto qV$ where V is the voltage on the two dees. The internal beam thus consists of a series of well-defined good-emittance ion beams of various energies convenient for measurements of nuclear[5] or atomic collision processes as a function of energy using suitable internal detector probes operating between the magnet sectors.

With cryo-pumping the cyclotron vacuum is typically 3 x 10^{-7} mbar (mostly H_2O and N_2). In the present experiments, three sets of ion gauges were installed and calibrated as a function of fringing field. The cyclotron cryo-pumps can then be valved off and a target gas introduced and brought to an equilibrium pressure, typically 10^{-4} to 10^{-6} mbar. A selected ion charge state is then accelerated through the target gas and the resulting ion characteristics (intensity and profile) are recorded with a differential radial beam probe. This is then repeated for different gas pressures. (A more complete description of the experimental arrangement is given in Ref. 4.)

Analysis

The attenutaton of the ion beam as a function of energy is given by

$$I(E) = I_0 \exp[-\sum_N \rho \,\Delta\ell\, \sigma(E)] \qquad (1)$$

where ρ is the target gas density (molecules/cm^3), $\Delta\ell$ is the path length between turns and $\sigma(E)$ is the beam-attenuation cross section, here assumed to be due to atomic charge-exchange, i.e. $\sigma(E) = \sigma_{\Delta q}(E)$. Since the VICKSI injector beam is stripped to q near the equilibrium charge state (i.e. $\sigma_{\Delta q>0} \approx \sigma_{\Delta q<0}$) at higher energies ($E>E_0$) one expects $\sigma_{\Delta q}$ to be dominated by electron-loss cross sections. Models of the latter predict $\sigma(E) \propto \beta^{-2}$ at high velocities.[3,6] The predicted β^{-2} dependence appears to be rather model independent as it arises presumably from phase-space considerations. At low velocities, and q less than the equilibrium value, electron capture dominates.[1] This is often the situation for conventional cyclotron beam attenuation measurements[7] and no simple velocity-dependence for σ can be employed, rather specific energy regions must be parameterized.[8]

We have used the following parameterization

$$\sigma(E) = \sigma_0(Z,q)\beta^{-n} \qquad (2)$$

for the effective cross section in Eq. 1 with the coefficients σ_0 and n adjusted to fit the data. Some results are displayed in Figs. 1 to 3. The data appear to be consistent with n=1.0±0.5. Even for the high velocity data (β>0.1) one observes an approximate $\beta^{-1.3}$ dependence, i.e. the cross sections decrease less rapidly than expected[3,6] and the beam is attenuated more rapidly with increasing energy than expected. This appears to be consistent with recent data[9] obtained at the LBL super-HILAC.

A simple phenomenological model which considers single- and multiple-electron loss from specific orbits has been developed and yields an approximate β^{-1} dependence for σ as is observed. This model will be described elsewhere.

Experiments with other combinations of ion projectiles and gases including energetic light ions (β>0.1) on heavy gases (e.g. krypton) are in progress.

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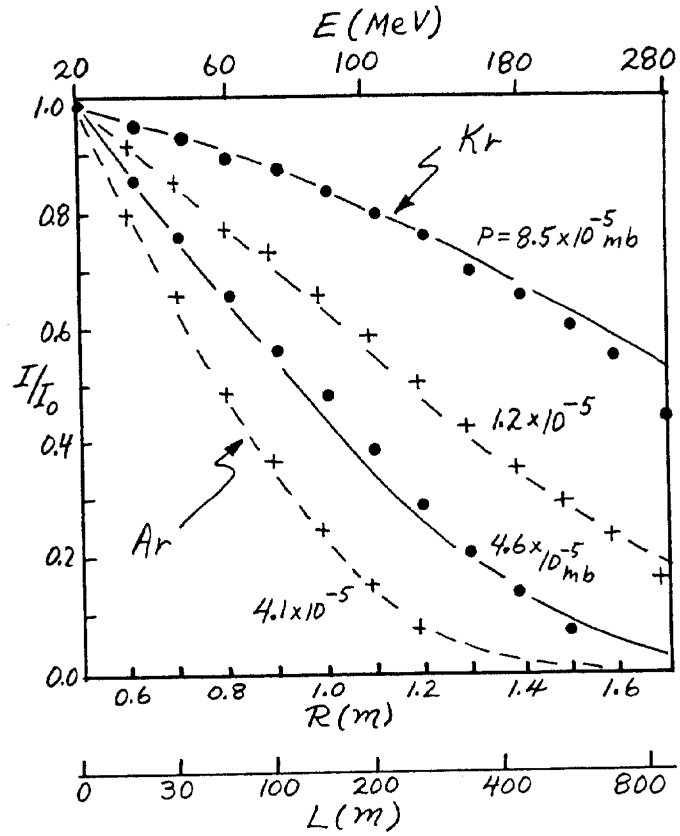

Fig. 1. Attenuation of $^{40}Ar^{10+}$ (E_f=290 MeV) in N_2 gas as a function of probe radius, R, path length, L, and energy, E. The curves are calculations using $\sigma=\sigma_0/\beta$ with $\sigma_0=2.1 \times 10^{-18}$ cm^2/mol.

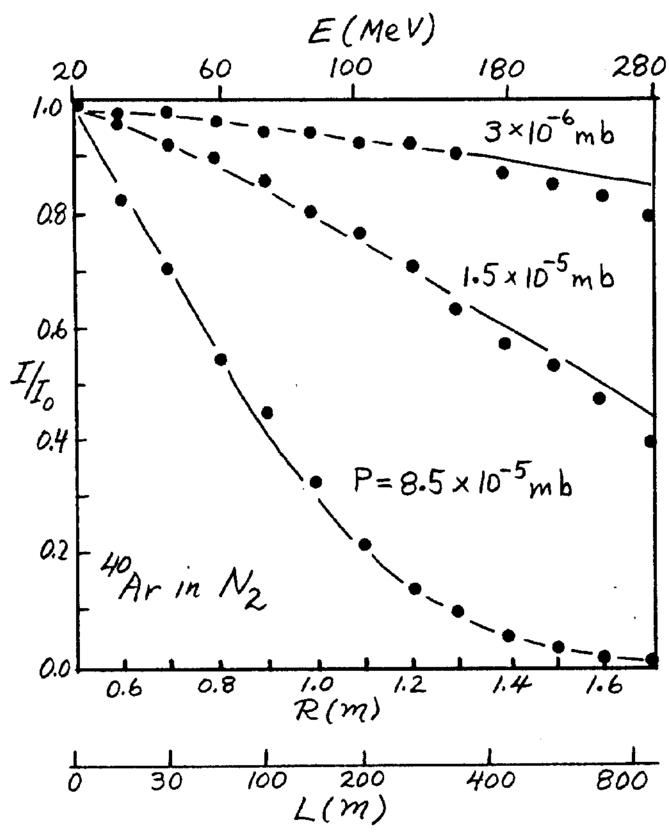

Fig. 2. Same as Fig. 1 for $^{40}Ar^{10+}$ in argon (+) and krypton (•) gas. The curves are calculations using $\sigma=\sigma_0/\beta$ with $\sigma_0=2.7 \times 10^{-18}$ cm^2/mol. and 5.5×10^{-18} cm^2/mol., respectively.

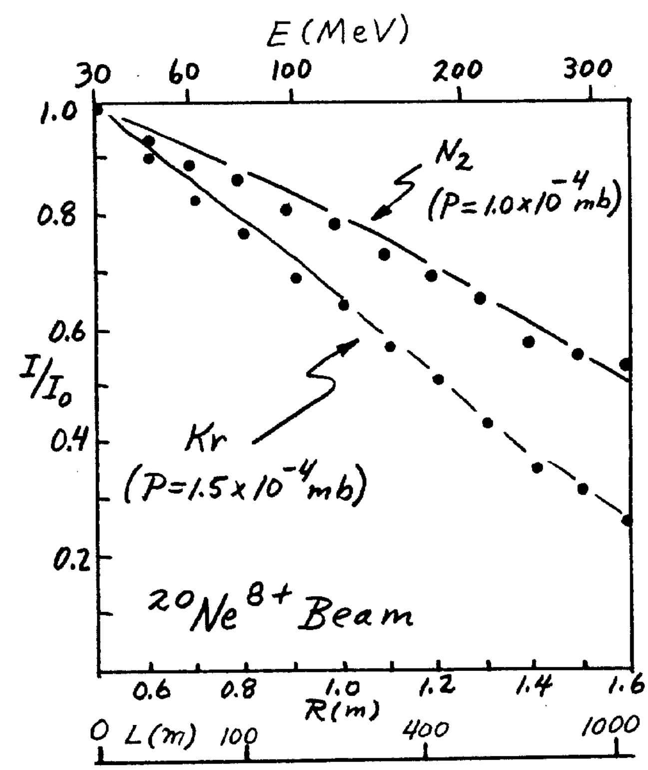

Fig. 3. Attenuation observed for $^{20}Ne^{8+}$ (E_f=392 MeV) in N_2 (top) and krypton (bottom). The curves are calculations with $\sigma=\sigma_0/\beta$ with $\sigma_0=0.31 \times 10^{-18}$ cm^2/mol. and 0.75×10^{-18} cm^2/mol. for N_2 and Kr, respectively.