

$Xe^{+n} - Xe^{+n}$ CHARGE-EXCHANGE EXPERIMENT USING A SPLIT-BEAM AND BEAM-INTERSECTION TECHNIQUE*

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Summary

We describe a design for colliding-beam charge-exchange experiments using the Xe beam that exits from the 1.5-MV Dynamitron of the Argonne National Laboratory Heavy-Ion-Fusion Facility.^{1,2} These experiments can be performed at any Xe beam energy as it becomes available, from 1.5 MeV to 10 MeV, and at any charge state from Xe^{+1} to Xe^{+8} .

Introduction

The idea is to split the original beam into two beams and bring them into collision with themselves. Some of the advantages of this approach are:

1. We need only one ion source and one accelerator.
2. We can study the charge exchange cross section of ions of virtually any charge state because the parent beam is energetic enough ($E > 1$ MeV) and beam strippers can be utilized.
3. We can scan a relatively broad range of center-of-mass colliding energies by changing the cross angle of the colliding beams.
4. The time structure of the Xe beam improves the signal-to-noise ratio and makes this method much more attractive than the conventional low-energy cross-beam experiments.

Beam Design

In order to make the discussion definite, we choose to work with Xe^{+1} ions of 2.3 MeV energy. We assume that the first Wideroe section is not yet operational,^{1,2} so the primary beam is the one exiting from the Independent Phase Cavities (IPC) section.

Initial Conditions

We start with the beam at the Wideroe entrance and specifically at the center of the first horizontal focusing quadrupole ($B' = 4,500$ gauss/cm, $L = 0.17$ m). Here we have as beam characteristics:³

- Geometric emittance: $\epsilon_x = \epsilon_y = 7.0\pi$ cm-mrad
- We assume upright ellipses with $x_0 = \pm 2.0$ cm and $y_0 = \pm 1.0$ cm
- Bunch length = ± 1.7 cm
- $\Delta P/P = \pm 1.9\%$
- Average current: $I_{av} = 40$ mA
- Instantaneous current: $I_{nst} = 40 \times 360^\circ/84^\circ = 170$ mA
- Duty cycle = $100 \mu s/1 s = 10^{-4}$

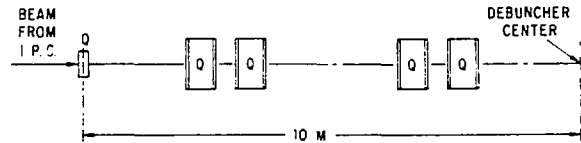


Fig. 1. Beam Line Section in Absence of First Wideroe Tank

Primary Beam Transport System

We substitute the Wideroe first tank with a 10 m long beam line. This beam line is composed of two horizontal and two vertical focusing quadrupoles (Fig. 1), and it matches the beam profile to the planned start of a previously-designed 8.5 MeV beam line⁴ at the center of the debuncher. At the center of the debuncher, we require a beam waist of 2.0 cm radius. We propose to use surplus ZGS quadrupoles.

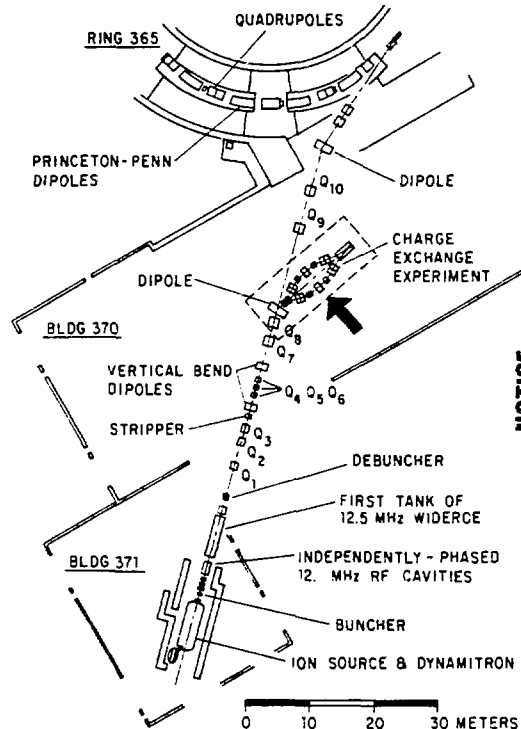


Fig. 2. The ANL H.I.F. Beam Development Facility

From the debuncher, we use the same beam line of Ref. 4 (Fig. 2) until past quadrupole Q8, where we

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introduce the dipole magnet 30VI36 to divert the beam into the charge exchange experiment (Fig. 3). From the debuncher to the stripper, we tune the magnetic elements to transport a 2.3 MeV Xe⁺¹ beam, while we tune the vertical translation system (Fig. 2) for a 2.3 MeV Xe⁺⁴ beam. In order to make the discussion definite, we have selected from the stripper output the Xe⁺⁴ ions; the vertical deflection system can, of course, be tuned to transmit downstream any one of the other available charge states.

probably be cheaper, especially if one has to buy all the magnets instead of using ZGS surplus. However, the magnetic system would be relatively "cleaner" from spurious electron background than the electrostatic one.

Reaction Rates

We assume that the stripper efficiency for Xe⁺⁴ is 20%. We choose to work with the average beam current since, by the time the two beams come into collision, the longitudinal beam spread, due to space charge repulsions, will effectively average out the 12.5 MHz beam structure. Then, the equivalent beam particle currents will be:

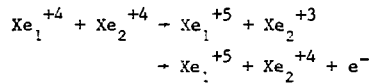
$$I_1 = 0.5 \text{ mA (beam \#1), and}$$

$$I_2 = 6.5 \text{ mA (beam \#2).}$$

To estimate the expected reaction rates, we summarize below the parameters used and the assumptions made:

- Beam current: $I_1 = 0.5 \text{ mA}$, $I_2 = 6.5 \text{ mA}$
- Crossing angle: $\theta = 17^\circ$
- Ion-Ion and ion-background gas cross section: $\sigma = 2 \times 10^{-16} \text{ cm}^2$
- Beam #1 height: $h_1 = 0.5 \text{ cm}$
- Beam #2 height: $h_2 = 1 \text{ cm}$
(for simplicity, we assume a uniform distribution for beam #2 and a rectangular profile)
- Reaction chamber operating pressure: $p = 10^{-10} \text{ Torr}$
- Particle velocity: $v = 1.8 \times 10^8 \text{ cm/s}$
- Total path ℓ of beam #1 between the two electrostatic deflectors (before and after interacting): $\ell = 10 \text{ cm}$

We choose to count only the beam #1 ions that have changed their charge state. For concreteness, we choose to count the Xe₁⁺⁵ of the reaction:



where indices 1 and 2 stand for beam #1 and beam #2.

The ion-ion charge exchange reaction rate R_{12} is given by the following expression:

$$R_{12} = \frac{\sigma I_1 I_2}{e^2 v \cos(\theta/2) h_1} \quad (1)$$

where $e = 1.6 \times 10^{-19}$.

The beam #1 residual gas reaction rate, $R_{1-\text{gas}}$, is given by:

$$R_{1-\text{gas}} = \frac{\sigma I_1 \eta_{\text{gas}} \ell}{e} \quad (2)$$

where η_{gas} is the residual gas number density per cm³.

Substituting with the appropriate values we find:

$$R_{12} = 1.4 \times 10^8 \text{ events/s average rate, and}$$

$$R_{1-\text{gas}} = 2.2 \times 10^7 \text{ events/s average rate.}$$

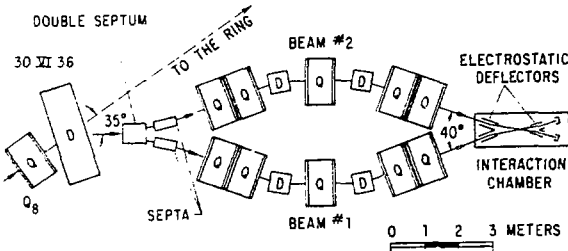


Fig. 3. Charge Exchange Experiment

Beam Splitter and Collider System

We tune the quadrupoles Q7 and Q8 to give an approximately parallel beam at the center of the dipole 30VI36 with a beam ellipses $x_0 = \pm 15 \text{ cm}$ and $y_0 = \pm 3.5 \text{ cm}$. The 30VI36 deflects the beam by about 35° and in a way to split the beam unequally as shown in Fig. 4. We choose beam #2 to be 13 times more intense than beam #1. The double septum deflects each part of the beam by 10° , and each of the single septa by 10° .

Each beam line is composed of five quadrupoles and two dipoles. This is a conservative design to assure beam achromaticity and isochronism in the collision region. We feel, however, that further detailed beam optics studies could reduce the number of the required bending and focusing elements.

The two beams finally enter the reaction chamber at a crossing angle of 40° . This angle is reduced to 17° by the electrostatic deflectors.

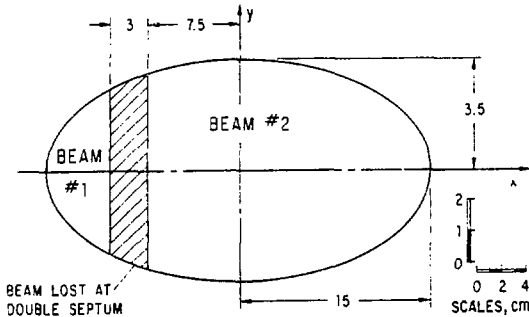


Fig. 4. Beam Envelope at the Double Septum Entrance

In the present description, we assumed magnetic quadrupoles and dipoles. A similar study has been undertaken using strictly electrostatic elements past the 35° bending magnet. The electrostatic system will

The signal-to-noise ratio

$$S = \frac{R_{12}}{R_{1\text{-gas}}} = \frac{I_2}{e v \cos(\theta/2) h n_{\text{gas}} l} \quad (3)$$

is independent of the intensity of beam #1 and increases with the instantaneous current of beam #2, provided that one could increase the pumping speed of the reaction chamber to keep n_{gas} fixed.

For our particular case, expression (3) gives a signal-to-noise ratio $S = 6$. This is quite comfortable for a successful cross section measurement. Workers in the past had succeeded in measuring charge exchange cross sections in cross beam experiments with signal-to-noise ratio as low as 10^{-3} or 10^{-4} .⁵ Of course, the lower theoretical limit is $S = \sqrt{N}/N$ where N is the total number of events, but it is quite difficult and lengthy to work too close to this limit.

Coming back to our case, even if we assume a 50% loss of the #2 beam due to collimation, etc., still the signal-to-noise ratio remains equal to the high value of 3.

The average electric current of the $\text{Xe}^{+(n+1)}$ produced is equal to

$$\bar{I} = R_{12} (n+1)e \quad (4)$$

For our case and $n = 4$, we get

$$\bar{I}_{\text{Xe}} = 1.1 \times 10^{-10} \text{ A} \quad (5)$$

This current could be measured with vibrating reed electrometers; however, by further reducing the intensity of beam #1, one can measure directly R_{12} using particle detection techniques.

Vacuum Considerations

Assuming that both beams stop inside the interaction chamber, the 7.0 mA total beam will be equivalent to the gas load of 1,250 (10^{-10} Torr) liter/s. Hence, if the Xe load is only due to the beam, a pumping speed of ~1,300 liter/sec will be enough to remove

all the Xe. This can be done with four 8 in. helium cryopumps ($4 \times 400 = 1,600$ liter/s). However, it would be important to dump the #2 beam outside of the interaction volume to avoid excessive sputtering and subsequent frequent shortings of the high voltage feedthroughs and particle detectors.

In order to secure a 1×10^{-10} Torr operating pressure in the reaction chamber, one should clean the vacuum walls with a glow discharge technique and bake out in situ at 400°C . Also, an additional ~30,000 liter/s zirconium-aluminum pump will be necessary to pump the desorbed gas from the walls (mainly hydrogen).

Finally, a differential pumping system will be necessary for both beam lines with a backable stainless steel pipe section from the last dipole magnet (Fig. 4) to the reaction chamber.

Acknowledgments

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