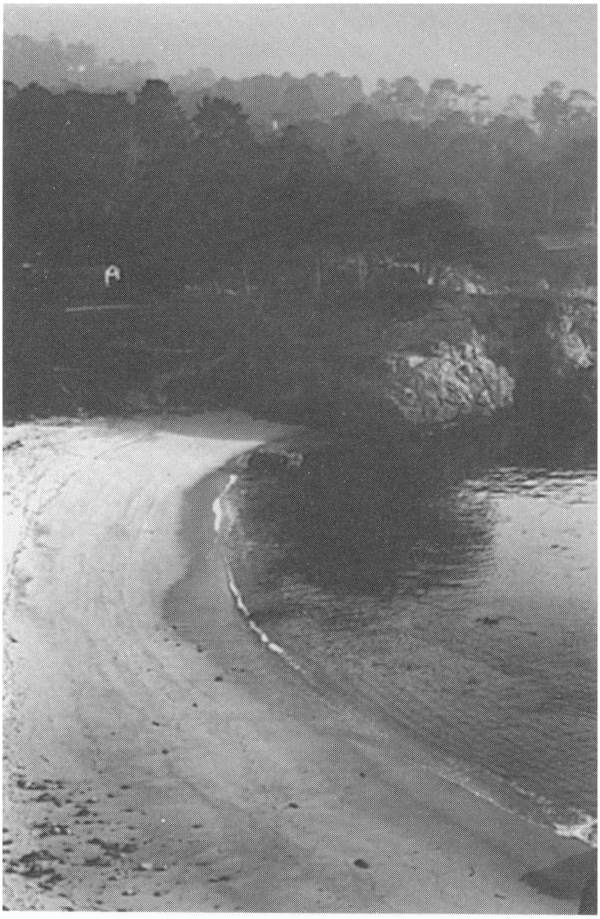
SECTION II

Ion Sources and Injectors



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CLUSTER BEAM ACCELERATION USING A TANDEM VAN DE GRAAFF

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A beam of accelerated clusters is one of the new tools for fundamental study of fusion reactions. We have investigated the possibility of cluster beam generation by using a tandem Van de Graaff. The key issue is the efficiency of transmission through the charge exchanger located in the high-voltage terminal. Cluster beams such as C_3 and Si_2 have been accelerated using a 1.7-MV NEC 5SDH-2 tandem Van de Graaff which is provided with a SNICS II sputter type negative-ion source. We have determined parameters that maximize the transmission of injected cluster beams. The charge exchanger is a canal filled with nitrogen gas. The nitrogen-gas feeding rate, the accelerating voltage, and the pumping speed of nitrogen from the charge exchanger are the factors which have been investigated in this work. We have observed transmission coefficients of 12 and 1.5% for C_3 and Si_2, respectively.

1 INTRODUCTION

The last fifteen years have seen a veritable explosion of cluster research brought about by new experimental advances in physics and chemistry[1,2]. Especially, new physics using atomic clusters with kinetic energy in the keV and even MeV region opens new perspectives for attractive application, because clusters are quasineutral, yet they can be accelerated, steered and focused by electromagnetic devices. For example, Schweikert *et al.*[3] suggested that the secondary ion emission can be enhanced by a large factor by means of cluster bombardment. A major concern is to maintain the integrity of the MeV-energy cluster during acceleration and beam transport. In the present work we have investigated how to generate carbon and silicon cluster beams with energies in the MeV range by using a tandem Van de Graaff. A sputter type source produces negative clusters such as C_n^-, F_n^- and Si_n^- where $n = 1, 2, 3, \ldots$ As is well known, a tandem has a big advantage: we can access the source very easily because it is located on an open platform with an electric potential as low as some 10 kV.

The problem with a tandem is the transmission of clusters through the stripper section in the tandem terminal and through the accelerating tubes with vacuum as low as 10^{-7} to 10^{-6} torr. In the following sections we describe the experimental setup and results of measurements performed to determine optimum parameters and discuss the result.

2 EXPERIMENTAL

Figure 1 illustrates the experimental arrangement. Cluster ion beams of carbon and silicon are generated by the SNICS II negative ion source. The cathode and extraction voltage are typically 7 kV and 15 kV, respectively. The 22-keV negative beams were analyzed by the switching magnet SW1 to define the mass of clusters. The 5SDH-2 type tandem is provided with a 500 l/s turbo pump at each end of the accelerating tubes.

The inset illustrates schematically the structure of the stripping system, which consists of a stripper canal with 6.35 mm ID and 635 mm length. Nitrogen gas is fed through a metering valve to the canal from the center. A baffle with a 6.35-mm aperture is mounted at the low energy end of the stripper to prevent the stripping gas from entering the low-energy accelerating tube. The stripper housing is provided with a titanium gettering system to pump the nitrogen gas. The sublimator contains heater coils which are powered by the generator. The heater current is adjustable by varying the rotating speed on the driving shaft of the generator. According to the data provided by the manufacturer[4], the gas pressure in the stripper canal changes linearly as a function of the housing vacuum. For accelerating the lighter heavy ions such as oxygen it amounts typically to 5×10^{-3} torr at a housing vacuum of 1×10^{-5} torr and 1×10^{-6} torr above the high energy turbo pump.

Backscattering experiments have been done to verify the purity of the cluster beams. A 60-nm thick gold target is located in the center of the scattering chamber. A 50-cm^2 surface barrier detector (SBD) counts scattered particles at 165° with respect to the beam direction. Particles detected by the SBD must have an energy E calculated as follows:

$$E = eU(1/m + 1/n), \quad (1)$$

where U denotes the terminal voltage, and m and n represent the number of atoms in a cluster as injected and as analyzed by SW2, respectively.

During the experiment the vacuum is kept better than 5×10^{-8} torr in the section between the ion source and the low-energy accelerating tube. A higher residual gas pressure of 3×10^{-7} torr was observed in the section after the high-energy accelerating tube due to the stripper gas bleeding.

A graphite cathode was used to generate carbon clusters, and a polycrystalline silicon for Si clusters. A series of clusters C_m^- or Si_m^- ($m = 1, 2, 3, \ldots$) was observed in the mass spectrum obtained by SW1. The total beam current was measured to be typically 10 μA with the Faraday cup FCS located at the entrance focus plane of SW1. We have chosen C_3^- and Si_2^- cluster beams for the present work. The cluster mass was restricted by the small intensity of carbon clusters heavier than C_3 and by the magnetic field of QD1 available for focusing silicon clusters. The electric current of C_3^- and Si_2^- amounted to 160 nA and 3 μA at the entrance of the tandem, respectively.

The electric current of accelerated clusters of C_n^+ ($n = 1, 2, 3$) and Si_n^+ ($n = 1, 2$) was measured at terminal voltages of 1.2 MV and 1.6 MV as a function of the pressure increase above the high energy turbo pump. The sublimator heater current was 30 A.

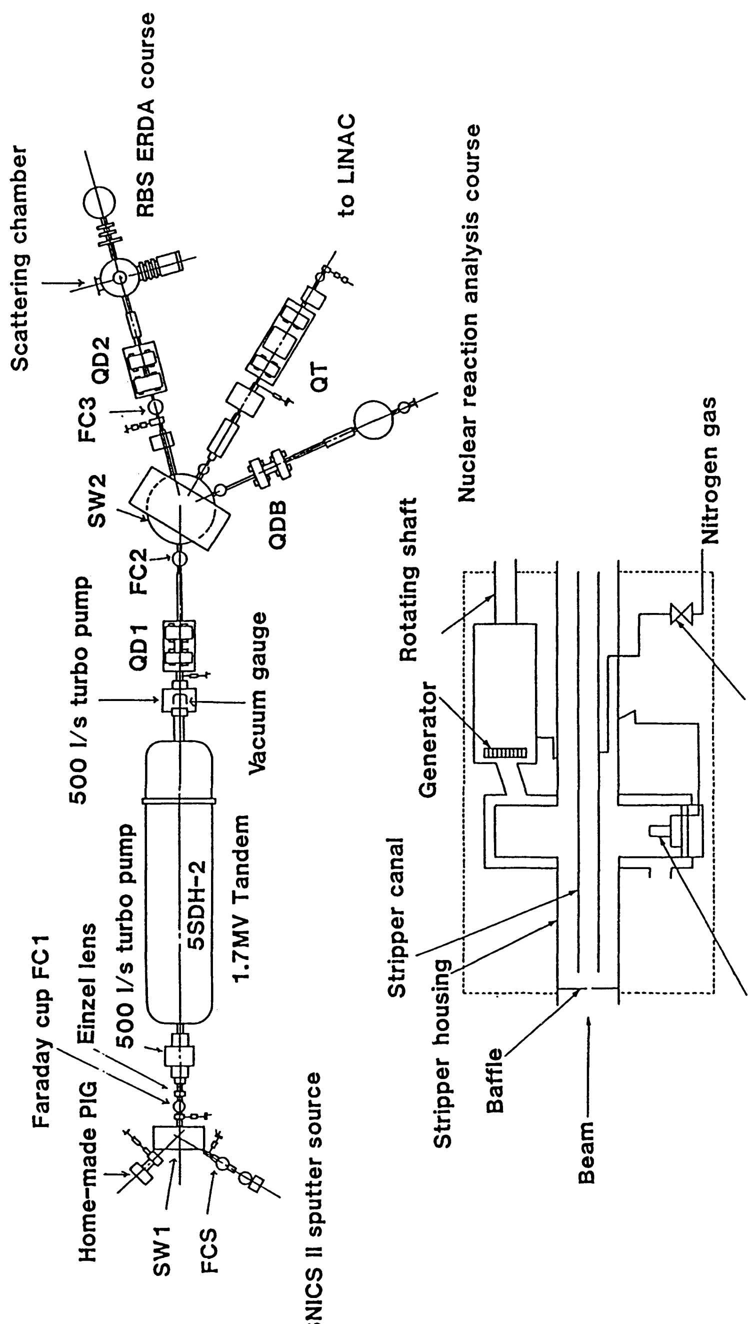

FIGURE 1 Layout of the experimental setup. The inset illustrates schematically the stripping system in the tandem terminal.

3 RESULTS

Figure 2 shows pulse-height spectra of particles scattered from the gold target, where a beam of C_3^- has been injected into the tandem, and C_n^+ clusters ($n = 1, 2, 3$) have been analyzed by SW2. The accelerating voltage was 1.6 MV. The peak positions agree with the values predicted by Eq. (1) within the uncertainty caused by the thickness of the gold target and the energy spread of the SBD for low-energy carbon ions. At low channel numbers a small amount of particles is observed. They have the same magnetic rigidity with analyzed clusters and have passed through QD1 and SW2. However, the disturbance from this impurity is negligible in this measurement.

Figure 3a represents the transmission coefficient of each carbon cluster beam C_n ($n = 1, 2, 3$) measured at a terminal voltage of 1.6 MV as a function of the increase in gas pressure observed on the high-energy-side turbo pump. The background vacuum is subtracted from the vacuum reading. The upper coordinate indicates nitrogen gas bled, which has been calculated from the pressure increase and the pumping speed of the turbo pump.

The transmission coefficient for C_3 amounts to only 4.4% at 0.6×10^{-7} torr. It shows, however, a maximum value of 12.5% at 1.9×10^{-7} torr. With increase of the stripper gas bleeding the transmission decreases until 1% at 6×10^{-7} torr. The peak is centered at 2×10^{-7} torr. This stripper gas bleeding is lower than that for accelerating light heavy ions such as $O^{2,3,4+}$ and $F^{2,3,4+}$ which require a pressure increase of about 1×10^{-6} torr on the turbo pump.

The yield of C_2^+, which are products of the breakup reaction $C_3 \rightarrow C_2 + C_1$, shows a maximum at 2.5×10^{-7} torr and decreases to 4% at 6×10^{-7} torr.

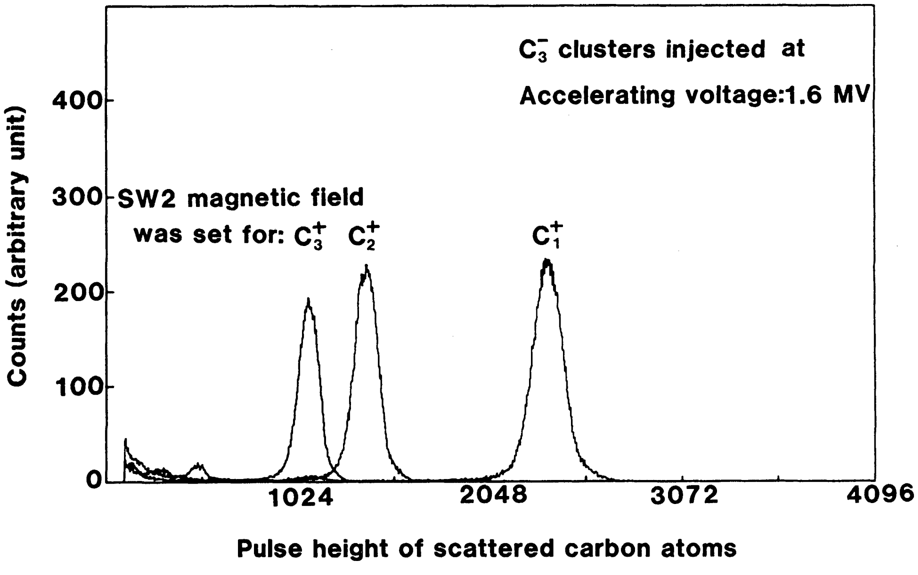

FIGURE 2 Pulse height spectra of carbon atoms produced from the backscattering of carbon clusters C_n ($n = 1, 2, 3$). C_3^- clusters are injected into the tandem with an accelerating voltage of 1.6 MV.

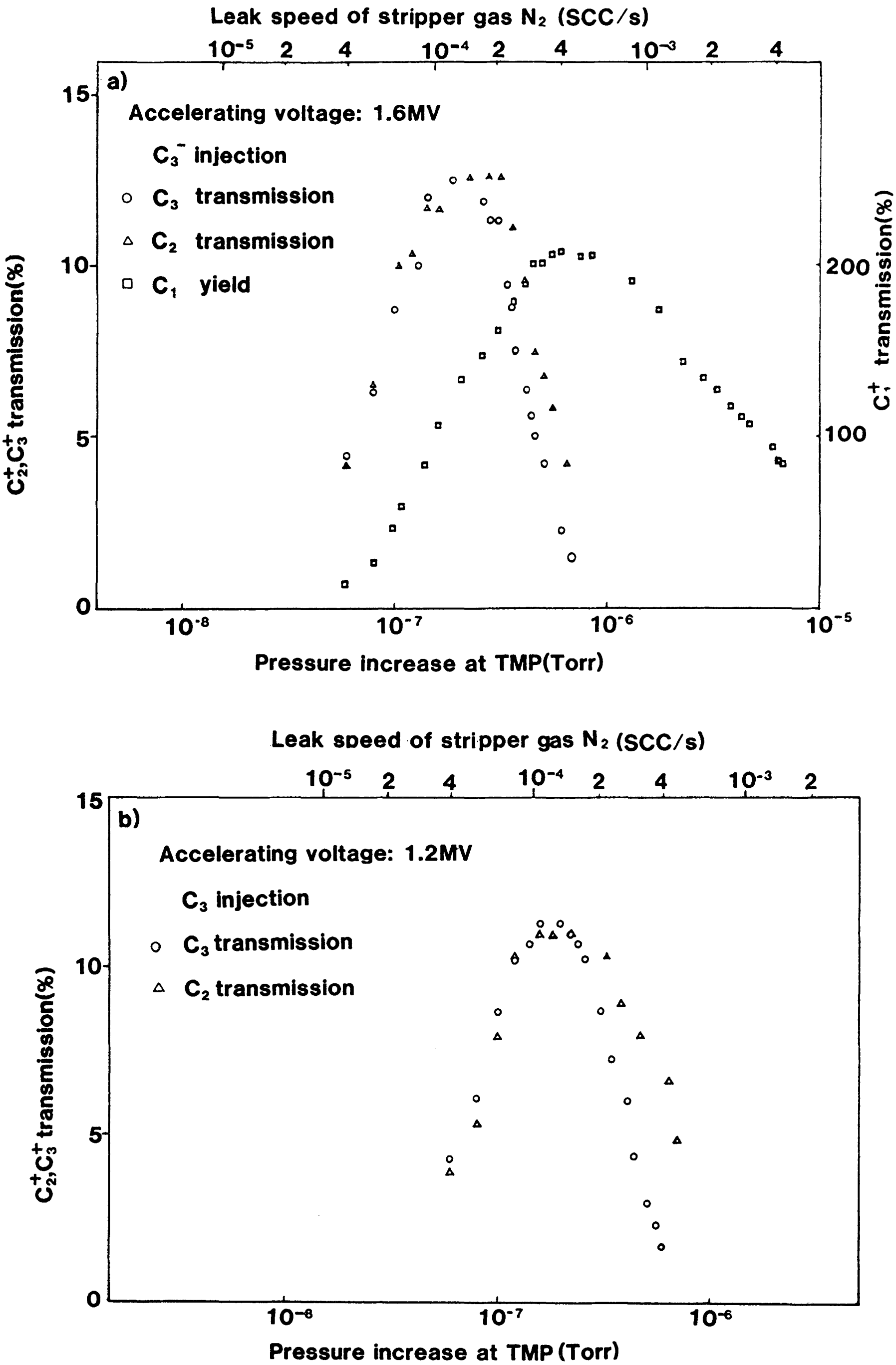

FIGURE 3 Transmission coefficients of C_n clusters ($n = 1, 2, 3$) as a function of the pressure increase above the turbo pump (stripper gas pressure in the canal). a) measured at 1.6 MV and b) at 1.2 MV.

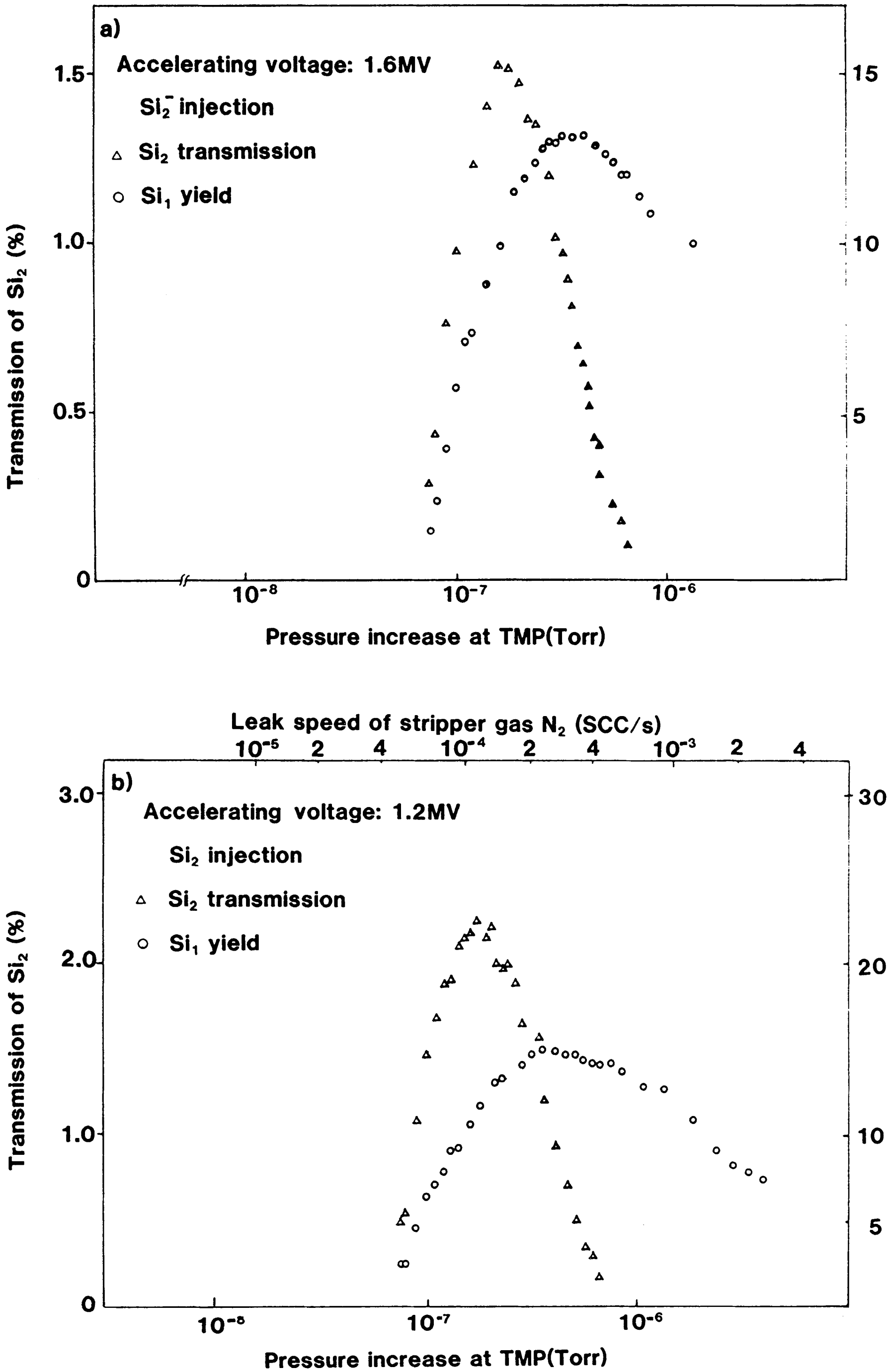

FIGURE 4 Transmission coefficients of Si_n clusters ($n = 1, 2$) as a function of the pressure increase above the turbo pump (stripper gas pressure in the canal). a) measured at 1.6 MV and b) at 1.2 MV.

The yield of C_1, products of the break up reactions $C_3 \rightarrow 3C_1$ and $C_3 \rightarrow C_2 + C_1$, increases from 10% at 0.6×10^{-7} torr to a maximum value of 200% of the injected C_3^- beam current at 6×10^{-7} torr. This high C_1 yield value is kept constant until 1×10^{-6} torr and decreases slowly with increase of stripper gas bled.

Figure 3b represents transmission coefficients of C_n^+ ($n = 2, 3$) measured at an accelerating voltage of 1.2 MV. Except for the accelerating voltage, all other parameters have been kept constant. The values of transmission coefficients for C_2^+ and C_3^+ have been reproduced by this experiment. This result indicates that the cluster energy has no large effect on the rate of charge exchange and on the breakup reactions of C_3 clusters in this energy region. We have omitted the yield curve of C_1 because there is no essential change in the 1.2-MV data in comparison with the 1.6-MV results.

Figure 4a represents the 1.6-MeV Si_2 measurement. The transmission of Si_2 (triangles) starts to increase at 7×10^{-8} torr and reaches a maximum value of 1.5% at 1.8×10^{-7} torr. After passing the peak it decreases rapidly to 0.1% at 7×10^{-7} torr. Products of the breakup reaction Si_1 (circles) show a broad peak centered around 3.5×10^{-7} torr and a long tail that reaches the vacuum region of 10^{-6} torr.

In Figure 4b triangles represent the transmission of 1.2-MeV Si_2 clusters, which show a maximum value of 2.3% around 1.8×10^{-7} torr.

The yield of charge exchange drops rather rapidly after passing the peak and amounts to 0.1% at 7×10^{-7} torr. The yield of Si_1^+ circles shows also a very long tail as observed in the 1.6-MV measurement. The peak value amounts to 15%.

The transmission coefficients of C_3 and Si_2 were measured as a function of the sublimator heater current. As a result of the measurements, the transmission for each cluster species has not been improved by increasing the pumping speed of the sublimator. The detailed explanation of the results is too lengthy to include here.

4 DISCUSSION AND CONCLUSION

The yield of charge exchange shows a maximum value at a pressure increase of 1.8×10^{-7} torr for both cluster species studied in the present work. This vacuum value corresponds to a nitrogen bleeding of 1.2×10^{-4} SCC/s (standard cubic centimeters per second) and to an estimated nitrogen pressure of 9×10^{-4} torr in the stripper canal. However, each cluster species shows a quite different yield value: the peak transmission coefficient is as high as 12% for C_3 clusters with energies between 1.2 and 1.6 MeV, whereas the peak value for Si_2 clusters is as low as 2.2% at 1.2 MeV and 1.5% at 1.6 MeV. It is also interesting to note that the Si_2 transmission increases with decrease of accelerating voltage.

Products of the breakup reaction C_2^+ show a yield curve which is shifted a little to the high gas bleeding side; however, the values are not different from those of C_3^+. The yield curve of C_1^+ has a maximum value of 200% at 5×10^{-7} torr, whereas that for Si_1^+ has a peak value of only 12–15%. In the stripper canal 12% of injected C_3^- clusters are charge exchanged and an additional 12% are broken up to $C_1 + C_2$. The rest of C_3 clusters are broken up to produce C_1^+. The charge exchange starts to produce multiply charged ions of carbon, and the C_1^+ yield begins to decrease with increase of the vacuum reading over 1×10^{-6} torr on the turbo pump. These figures suggest that a tandem is one of the practical accelerators for generation of cluster beams with energy in the MeV regime. However, Si_2 clusters are more unstable than C_3 clusters and are broken up heavily in the stripper section, and only 1.5–2.2% of the Si_2^+ is available for cluster experiments. The lower value of Si^+ yield can be explained by the preferential production of multiply charged silicon ions at the gas pressure in the stripper canal, which is as low as 1×10^{-3} torr.

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