CHARGE FRACTION OF 6.0 MEV/N HEAVY IONS WITH CARBON FOIL: DEPENDENCE ON THE THICKNESS

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Abstract

The NIRS-HIMAC injector produces various ion species between H and Xe, and accelerates them up to 6.0 MeV/n. At this energy they are stripped with a carbon foil before being injected into two synchrotron rings. The thickness of the foil has so far been fixed at 100 μg/cm^2 for all ion species, though it has not yet been optimized regarding the stripping efficiency, particularly for ion species heavier than Si. In order to find the optimum thickness at the equilibrium charge state, measurements of the charge fraction have been made for the thickness range between 10 and 350 μg/cm^2. Two of results were quite interesting: the intensity of Ar^{18+} ions was improved by a factor of 2 under the optimum thickness (~350 μg/cm^2); for Fe ions, the thickness for the equilibrium charge state was only 100-150 μg/cm^2.

1 INTRODUCTION

At the NIRS-HIMAC injector [1], we precisely measured the charge fraction and distribution of heavy ions after stripping with a carbon foil at an energy of 6.0 MeV/n, which corresponds to a velocity of 15.1 atomic units. Much effort has been made to develop an apparatus and to find each optimum thickness of the carbon foil for various ion species from C to Xe regarding the stripping efficiency and beam quality. The results were also compared with those obtained at other facilities and with the calculations developed by Rozet [2], which are applicable to ions lighter than Ar.

Beams of 8 keV/n heavy-ion are produced at three ion sources before being accelerated up to 6.0 MeV/n by both the RFQ (8-800 keV/n) and Alvarez (0.8-6.0 MeV/n) linacs. When designing the HIMAC 10 years ago or earlier, there were few data or information concerning the stripping efficiency at such a high-energy region. Since then, a fixed thickness (100 μg/cm^2) has so far been used for all ion species without optimization regarding the efficiency, particularly for ion species heavier than Si. A primary motivation in this work is this optimization. In addition, great interest has been focused on "what is the maximum charge fraction after stripping" that can be practically used regarding the intensity, particularly for ions heavier than Fe.

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Recently the apparatus has begun to work successfully. The expected data for several ion species have been obtained for the thickness range between 10 and 350 μg/cm^2 with some new results, which are presented and discussed in this article. For example, an increase in the thickness from 100 to 350 μg/cm^2 allowed us to improve the yield of Ar^{18+} ions by a factor of 2 with no reduction in their transmission efficiency or in the injection efficiency into the synchrotron.

2 APPARATUS AND METHODS

2.1 Layout of the apparatus

Figure 1 shows a schematic layout of the apparatus. The beam passing through the carbon stripper foil (CSF) generally has several fractions with different charge-to-mass (*q/m*) ratios. They are analyzed by 20° pulsed switching and 70° DC bending magnets before being measured at a Faraday cup (FC-2) regarding their peak intensity (current). There is a horizontal slit just upstream of FC-2, of which the width is usually set at 10 mm, while the beam size is a few mm. When sweeping the magnetic field (B) under this condition, the measured peak intensity is proportional to each charge fraction that can be obtained from the ratio of each peak to the total of all peak values.

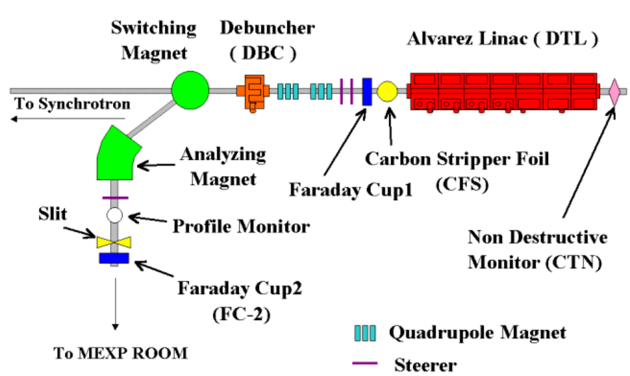

Figure 1: Layout of the apparatus.

The momentum resolution is about 1/2000, which allows us to clearly separate the isotopes of Xe. The sweeping of B is controlled by a Hall detector, thus covering all observed *q/m* values. The other elements in the beam transport line between CSF and FC-2, such as the Q-magnets and steering magnets, are also swept in the same way. An example of the measured charge distribution is shown in Fig.2.

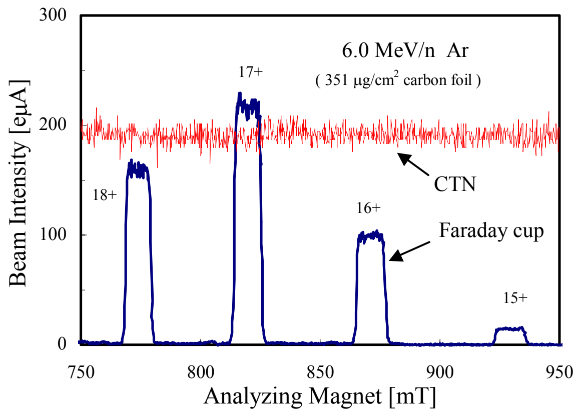

Figure 2: The measured charge distribution for Ar. It is used to obtain the charge fraction, after compensation by the CTN monitor and averaging the peak values.

A capacitive pickup-type non-destructive beam monitor (CTN) [3] detects the fluctuation in the beam intensity upstream of the Alvarez linac, and compensates the measured value at FC-2. This fluctuation is due mainly to that of ion sources, which is normally on the order of ±10%, and can't be easily reduced. The amplitude of signals from this CTN is proportional to the peak beam intensity between 5 and 500 eμA. Since the actually used beam intensity was 50-500 eμA, this compensation can be successfully made within an adequate accuracy. The fluctuation in the transmission efficiency of the Alvarez linac depends on neither the ion species nor their intensity; it is normally fixed at 92%, as long as the intensity is less than 500 eμA.

2.2 Transmission efficiency (η) of beams in the apparatus

The transmission efficiency (η) between FC-1 and FC-2 was measured in order to know the beam loss in this beam line; η was 90% without CSF, and 85-88% with CSF, depending on both the ion species and thickness of CSF. The additional beam loss (Δη) due to CSF can thus be evaluated to be 2-5%, which is due mainly to an emittance growth or an increase in the momentum spread when using CSF. However, this Δη should not fluctuate among fractions for one ion species using a particular thickness under a constant beam intensity. Although the emittance value of the beams from three ion sources varies widely, it is always defined as 150 πmm×mrad at the RFQ; this value is quite smaller than the acceptance of Alvarez; hereafter, the value of 90% should be applicable to cases for all ion species. At present, the overall error for the measurement of the charge fraction is dominated by the reading error at FC-2 than others, which is estimated to be on the order of 1%.

2.3 Measurement of the thickness of carbon stripper foils (CSF)

The thickness of CSF measured by the maker was compared to the measured value in this work. Our method is to measure the difference in Bρ (momentum) values of the N^{6+} beam between with and without CSF by using a profile monitor just upstream of FC-2. The difference is once converted into that of energy loss, then translated into the thickness by using an authorized table for the stopping power [4]. The precision of the profile monitor is 0.1 mm, which corresponds to a resolution in energy loss of 0.6 keV/n and in thickness of 2.9 μg/cm^2. Table 1 summarizes the thickness of the used CSFs. The difference in thickness between the two methods was −13~+19% for all used CSFs; hereafter, the values measured by our method are used for discussions.

Table 1: Thickness of carbon stripper foils (unit: μg/cm^2).

Catalogue value	the measured value by the maker	the measured value in this work
10	8.9	11
20	22.6	20
30	30.9	28
40	42.9	39
50	53.2	52
100		89
100	98.1	115
150		166
200	192	206
250		255
300	317	329
300	322	351

3 RESULTS AND DISCUSSION

Figs.3 (a)-(e) show the charge fraction vs. thickness of the CSFs for various beams (C, Ne, Si, Ar and Fe) at 6.0 MeV/n. The calculated results are also directly shown by the solid lines, except for Fe. For C in Fig.3 (a), the fraction of C^{6+} (C^{5+}) reaches an equilibrium state at thickness larger than 50 μg/cm^2, and is 98% (2%), which agrees well with both Shima's data of 97.67% (2.33%) at 5.983 MeV/n [5] and the calculation of 97.9% (2.1%) at 6.0 MeV/n.

The measured fractions of fully stripped ions for Ne~Ar ($10 \le z \le 18$) were quite smaller than those of the calculations. In addition to this disagreement, their differences become large as the atomic number (z) of incident ions increases. The fractions, except for those of fully stripped ions, are also consistent with these results. For an example in the case of Ar, the fraction of Ar^{18+} (Ar^{17+}, Ar^{16+}, and Ar^{15+}) was 33% (44%, 20%, and 3%) at a thickness of 329 μg/cm^2, while that of calculation was

45% (40%, 14%, and 1%). Such a tendency can also be clearly seen for the other ion species, which suggests that the precision of the used data (cross sections) for ionization, capture, excitation is still unsatisfactory, particularly for ion species heavier than Ne (z=10).

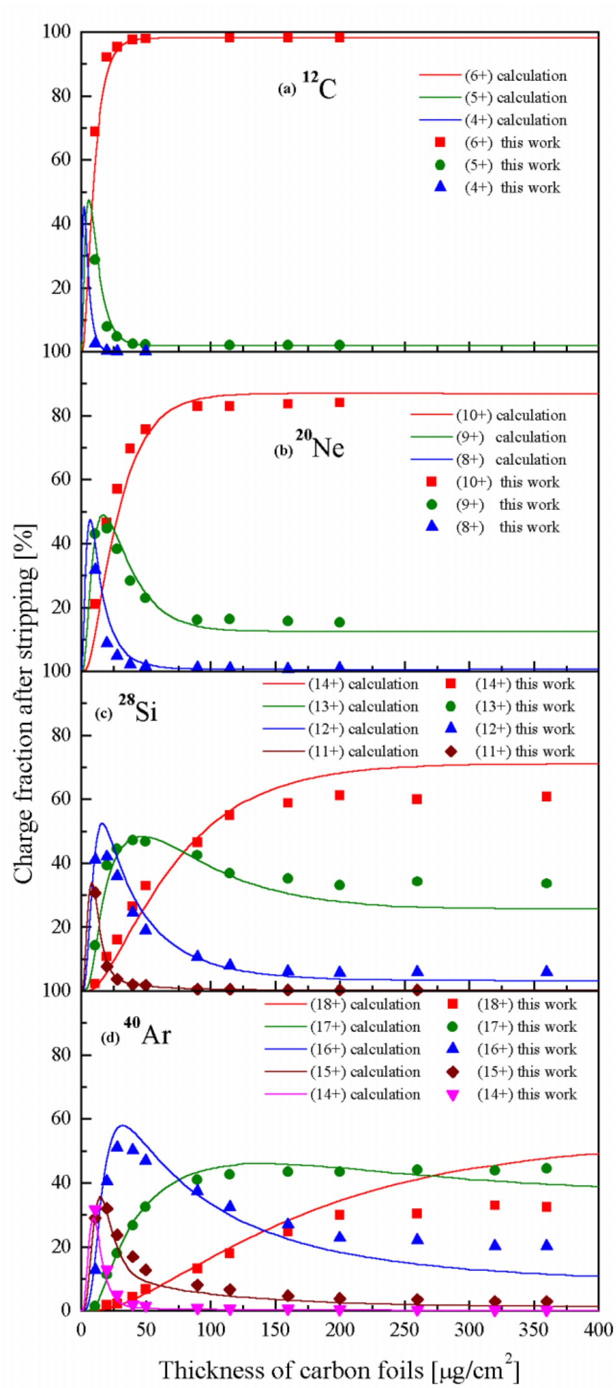

Figure 3(a): the charge fraction vs. thickness of the CSFs for ^{12}C beam, (b) ^{20}Ne, (c) ^{28}Si and (d) ^{40}Ar.

For 6≤z≤18, the thickness of equilibrium charge state increased from 50 μg/cm^2 to 350 μg/cm^2 or more as the z number became large, while it rapidly decreased to 100-150 μg/cm^2 for z=26. In the case of the former (z≤18), an equilibrium (charge state) condition is obtained when all electrons including those in the K-shell are balanced regarding ionization and capture; it is possible to efficiently remove all these electrons, due to their small binding energies. In the latter, however, there is little possibility to remove the K-shell electrons due to their large binding energies. In this case, the equilibrium condition should be determined primarily by the behavior (ionization/capture) of the L- and outer-shell electrons. Since their interaction cross sections are much larger than those of the K-shell electrons, such a small thickness allows obtaining an equilibrium condition. Further interest is focused on information for 19≤z≤25 (K~Mn) at the 6.0 MeV/n region, though the related results have so far been very few, as far as we know. We will try to obtain them, though it depends strongly on the capability of ion sources to produce of metallic ions.

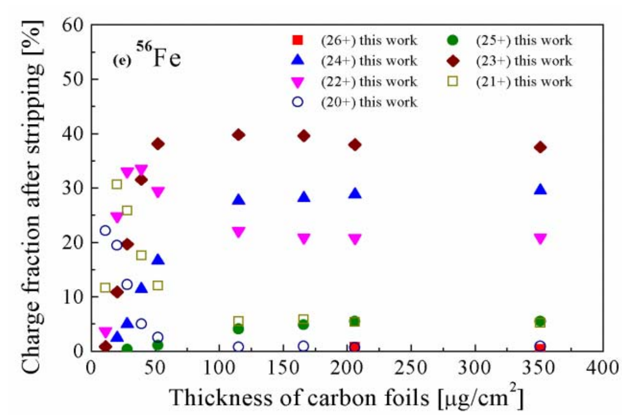

Figure 3(e): the charge fraction vs. thickness of the CSFs for ^{56}Fe beam.

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