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The charge state distribution of a carbon beam measured at the lund pelletron accelerator with the newly installed terminal pumping system in use

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Abstract

Charge state distributions for ^{12}C and ^{13}C ions have been measured at the Lund Pelletron tandem accelerator for the N_2 gas stripper with a newly installed terminal pumping system in use. A comparison of the results obtained for the ion energies between 1.5 and 2.8 MeV with the foil stripper and the gas stripper without terminal pumping demonstrates the great improvement of the stripping process achieved with the new terminal pumping.

1. Introduction

In most types of experiments using a tandem electrostatic accelerator, it is valuable to know the distribution in the beam of the charge states obtained in the stripping system at the accelerator high voltage terminal. With the knowledge of the distribution it is possible to optimise the selection of the terminal voltage and the suitable ion charge state for each experiment.

In most tandem accelerators both foil and gas strippers are available. The advantage of a gas stripper compared to a foil stripper is the better stability of the transmission over time. Due to radiation damage, the transmission through a foil will constantly alter. The disadvantages of gas stripping are a lower beam transmission and a lower mean charge state at a given terminal voltage.

As the negative ions enter the stripper medium, a certain distribution of the positive charge states will result. This distribution will change with depth until, at a certain depth, equilibrium between the different charge states is reached. This equilibrium distribution [1] is to a first approximation a function of the nuclear charge and the velocity of the ions [2]. When the positive ions are accelerated from the terminal potential to ground potential, ions of different charges acquire different energies. With a simple particle detector placed in the beam pipe after the accelerator, and by detecting the elastically backscattered ions in a suitable target, it

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is possible to distinguish between different charge states by their energy. A few years ago measurements of the distribution of charge states were performed at the Pelletron in Lund [3–5] using this technique for both foil and gas strippers and with ions of interest for our Accelerator Mass Spectrometry (AMS) programme.

Terminal pumping has been recently installed in the Lund tandem accelerator [6,7]. With this equipment the stripper gas leaking out of the stripper chamber is recirculated back to the stripper chamber instead of being transported away through the accelerating tubes. In this way, a higher gas pressure can be used in the stripper chamber and better vacuum conditions are maintained in the accelerator tubes. This installation has greatly extended and improved the possible uses of a gas stripper for heavy ion AMS experiments [8].

In this paper measurements of charge state distribution performed using N_2 gas as stripper medium, including terminal pumping, are reported. ^{12}C and ^{13}C ions were used, as carbon is the ion most frequently employed for AMS at the Lund Pelletron. These measurements are also a first test of the performance of the terminal pumping system and give the direction of further development.

2. Experimental procedure

The outline of the experimental set-up is given in Fig. 1. The target chamber was placed approximately 3 m after the accelerator tank and 1.5 m in front of the analysing magnet. A movable belt with 50 positions for targets and also for a collimator was assembled in the target chamber in order to be able to make fast changes between the targets and the collimator. A 25 nm thick layer of gold was evaporated onto a $26 \times 30\,mm^2$ glass or perspex plate. Three different targets were employed for each measurement in order to minimise influences of inhomogeneities in the gold layers. An ion beam emerging from the terminal stripper impinged on a gold target and the elastically scattered ions were detected with a common photodiode detector. The measurements were made simultaneously for all charge states, thus avoiding normalisation problems for the different charge states. Prior to the measurements the collimator was used to focus and to centre the ion beam onto the target position.

The windowless photodiode with an active area of $13\,mm^2$ was placed approximately 100 mm from the target and positioned at an angle of 165° with respect to the beam. An aperture, 3 mm in diameter, was placed 5 mm in front of the detector

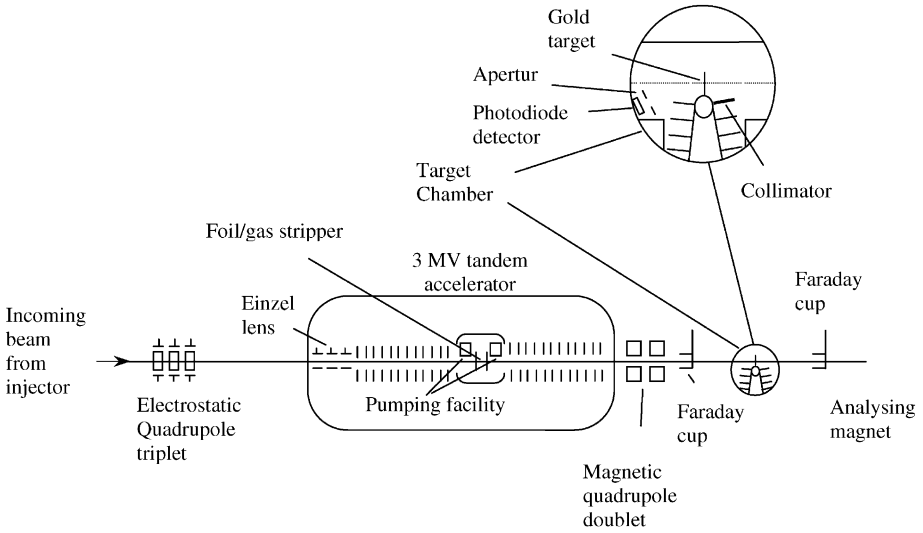

Fig. 1. The accelerator and the experimental set-up.

to reduce the count rate and to obtain a well-defined solid angle. The distribution of the elastically scattered ions from the gold foil will not be affected by ions scattered in the substrate because the kinematic factor and the backscattering cross-section are both an order of magnitude lower for backscattering from the substrate than from the gold target. Normal electronic equipment was used to register the pulse-height distributions.

3. Measuring procedure

These measurements were done at two different thicknesses of the stripper gas (the "thickness of the stripper gas", often expressed in the unit of $\mu g/cm^2$, means the density of the gas (in $\mu g/cm^3$) multiplied by the distance (in cm) that the ions pass through in the gas): a thickness at which the ion beam will not reach the final distribution of charge states at the given beam energy. This thickness will be referred to as the non-equilibrium thickness and, a thickness at which the ion beam will reach the final distribution of charge states at the given beam energy. This thickness will be referred to as the equilibrium thickness. At a certain terminal voltage (2.4 MV) the charge state distribution was also measured as a function of the thickness of the stripper gas between 0.1 and $0.9\,\mu g/cm^2$, both with and without the terminal pumping in operation.

The measurements of the charge state distribution were made in steps of 100 kV for terminal voltages between 1.5 and 2.8 MV, i.e. the ion energy at the stripper was varied between 1.5 and 2.8 MeV. In order to avoid interference from ^{12}C ions (resulting from the break-up of the molecules in the terminal) when ^{13}C measurements are being done, a ^{13}C sample enriched to $>90\%$ was used[1] in the ion source. For ^{12}C isotope measurements a pure graphite sample was used.

Due to residual gas on the high energy side of the accelerator tube, the charge state distribution obtained in the stripper medium will change slightly before the beam reaches the experimental chamber. The results obtained in these measurements are of value when selecting the charge state by the analysing magnet, but obviously cannot be compared directly with measurements done immediately after a stripper medium.

Prior to performing the backscattering measurements, a collimator 8 mm in diameter was placed in the gold target position and the beam was optimised to a maximum current in the Faraday cup located approximately 1.3 m behind the collimator. When the collimator is removed, an increase in current in the Faraday cup of up to 20% was accepted (at the greatest thickness of the gas stripper, giving a somewhat wider beam divergence due to the increased number of residual gas molecules in the high energy accelerator tube, a 30% increase in current was accepted). In this way it could be assumed that very close to 100% of the beam was hitting the target, taking into consideration that the area of the collimator aperture was only 10% of the target area. This beam check procedure with the collimator was repeated every time the optical conditions were altered. Since the focusing of the high-energy tube of the accelerator and the magnetic lens just after the accelerator acts more strongly on higher charge states, it is important to verify that all the different charge states hit the target. The distribution profile perpendicular to the beam axis for different charge states has therefore been measured [5].

No vacuum gauges are located in the high voltage terminal during normal machine operation. The thickness of the stripper gas medium was therefore measured indirectly during the experiment by observing the pressure in the beam tube on both sides outside the accelerator tank. The relation between these pressure values and the pressure in the stripper gas was obtained by installing a temporary gauge in the high voltage terminal during maintenance, as reported in Ref. [9].

The rotational speeds of the turbo molecular pumps in the high voltage terminal were 19,000 and 20,000 r/min (revolutions per minute) for the pump before and after the stripper chamber, respectively. The pump speeds were constant to within 500 r/min.

[1] Kindly provided by Dr Manfred Friedrich, FZR, Dresden.

4. The Rutherford backscattering cross-sections

Since the Rutherford backscattering (RBS) cross-section is energy dependent, the number of counts obtained in the detector for each charge state must be corrected. In order to apply the RBS cross-section to the measured data, the validation of the cross-section must be checked for the energy interval used in this investigation. The energy interval of the ions must be high enough to avoid screening effects from the electron shells and sufficiently low not to initiate nuclear reactions.

The low energy criterion is checked by ensuring that Lindhard's magic $t^{1/2}$ parameter [10] is greater than ~ 10. The expression for $t^{1/2}$ is given by

$$t^{1/2} = \varepsilon \sin(\varphi/2)$$

where φ is the centre-of-mass scattering angle and ε is a dimensionless energy parameter from the Lindhard-Scharff-Schiøtt (LSS) theory [11] given by

$$\varepsilon = \frac{A_2}{A_1 + A_2} \frac{0.8853 a_0}{Z_1 Z_2 e^2 \sqrt{Z_1^{2/3} + Z_2^{2/3}}} E$$

where Z_1, A_1, Z_2 and A_2 are the atomic numbers and atomic masses of the incoming ions and the target atoms, respectively, e is the elementary charge, a_0 is the Bohr radius and E is the energy of the incoming ions. In this investigation the low energy criterion is fulfilled as $t^{1/2} > 50$.

According to Ref. [12], the lower energy limit for nuclear reactions to occur can be roughly calculated using

$$E = 1.44 \frac{A_1 + A_2}{A_2} \frac{Z_1 Z_2}{(1.25(A_1^{1/3} + A_2^{1/3}) + 5.1)}$$

with the same notations as above. For a carbon beam scattered from a gold target, the RBS cross-section is valid up to an energy of 48 MeV, i.e. the high energy criterion is also fulfilled in this investigation.

5. Results

5.1. General

Fig. 2 shows pulse-height distributions for ^{12}C and ^{13}C ions for various conditions but at the same terminal voltage, namely, 2.4 MV. In Figs. 2a and b the charge state distribution for ^{13}C is shown with terminal pumping, at equilibrium and non-equilibrium gas stripper thickness, respectively. In Fig. 2c the charge state distribution of ^{12}C ions for foil stripping is shown. In Fig. 2d the ^{13}C charge state distribution at non-equilibrium gas stripper thickness without terminal pumping is shown. It can be noted that in Fig. 2d the lowest detectable charge state is C^0, which will henceforth be referred to as the neutral component, while in Figs. 2a–c the neutral component has vanished into the background.

The pulses between the peaks that form the low-energy tails are C ions, which have lost part of their energy in elastic collisions with residual gas molecules leaking from the stripper system into the accelerator tubes. The particles in the low-energy part of the distribution probably originate from residual gas molecules charged in elastic collisions near the high voltage terminal and then accelerated to ground potential with energies up to about 2.4 MeV, i. e. the maximum energy that a single charged particle can acquire at the terminal voltage of 2.4 MV. It should be noted that the low-energy background and the background between the peaks are much more pronounced when the gas stripper is used than when the foil stripper is used, since the gas diffuses out of the stripper chamber along the beam tube, in particular when the terminal pumps are turned off.

The widths of the peaks in the pulse-height distribution are determined by the resolution of the detector and the electronics, the voltage stability of the accelerator and the thickness of the gold foil. For carbon ions of several MeV, the resolution of the detector and the electronics is of the order of 60 keV, while the high voltage stability of the accelerator will contribute less than 10 keV. The major contribution is introduced by the thickness of the gold target, and the overall width

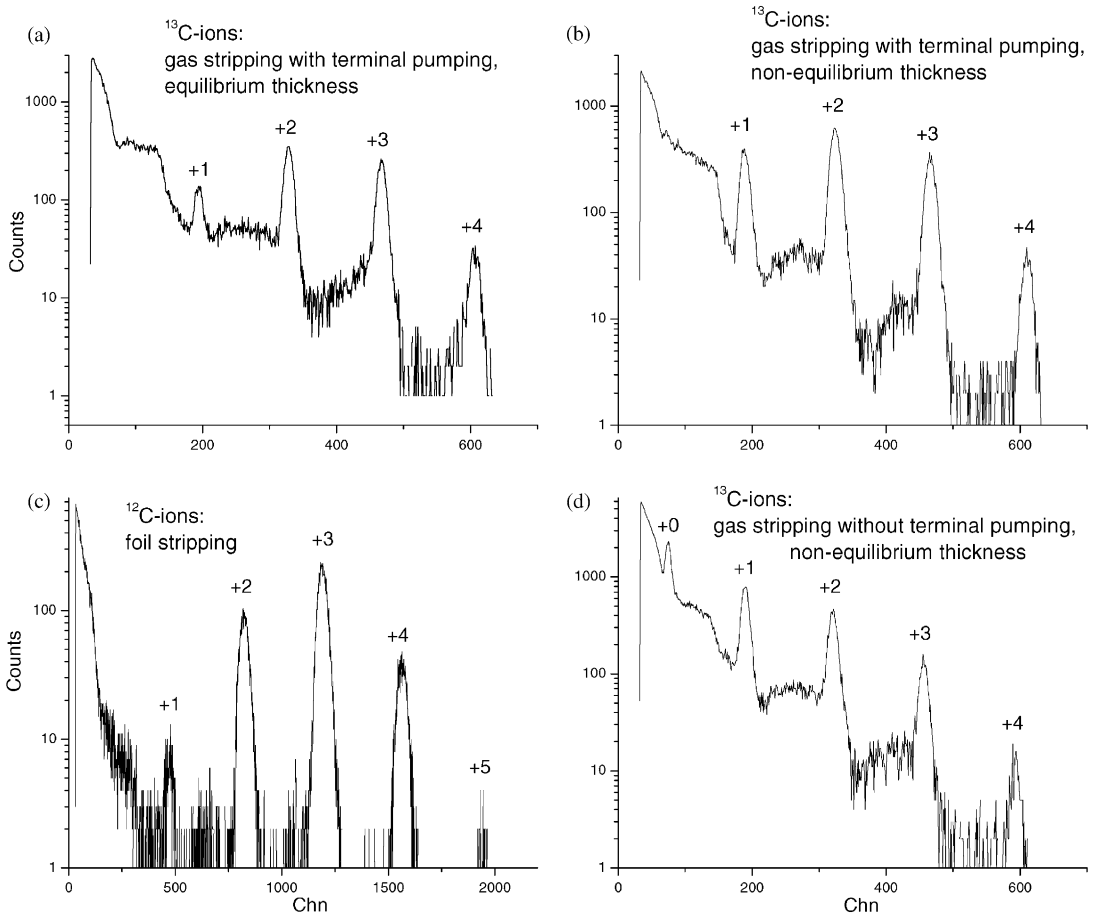

Fig. 2. Pulse height distributions obtained at a terminal voltage of 2.4 MV and for various stripper media and various thicknesses of the media. (a) *a* ^{13}C charge state distribution at equilibrium thickness, (b) *a* ^{13}C charge state distribution at non-equilibrium gas thickness. Both distributions *a* and *b* are for the gas stripper with terminal pumping, (c) *a* ^{12}C charge state distribution using a foil stripper, (d) *a* ^{13}C charge state distribution obtained with gas stripper without terminal pumping at non-equilibrium gas thickness.

is approximately 260 keV at a target thickness of 50 μg/cm^2 for carbon ions.

5.2. Non-equilibrium distribution

In Fig. 3 the charge state distribution for ^{12}C is given as a function of the thickness of the gas stripper, measured with the terminal pumps operating and for a terminal voltage of 2.4 MV. The equilibrium state is reached at a thickness of approximately 0.63 μg/cm^2. One can note a fast decrease of the neutral component and an increase of the mean charge with increasing gas thickness.

In Fig. 4, the charge state distribution for ^{13}C as a function of incident ion energy is shown at a stripper gas thickness of 0.28 μg/cm^2 (see the arrows in Fig. 3). According to Fig. 3, the equilibrium state is not reached at this thickness and the fraction of charge number 3+ is approximately 45%. The fraction of the neutral component was too small to be extracted from the high background. The fraction of charge state 5+ was too low even at the highest energies to be detected in the pulse-height distribution.

The slightly wave-like behaviour of the measured charge distribution, as seen in Fig. 4, could

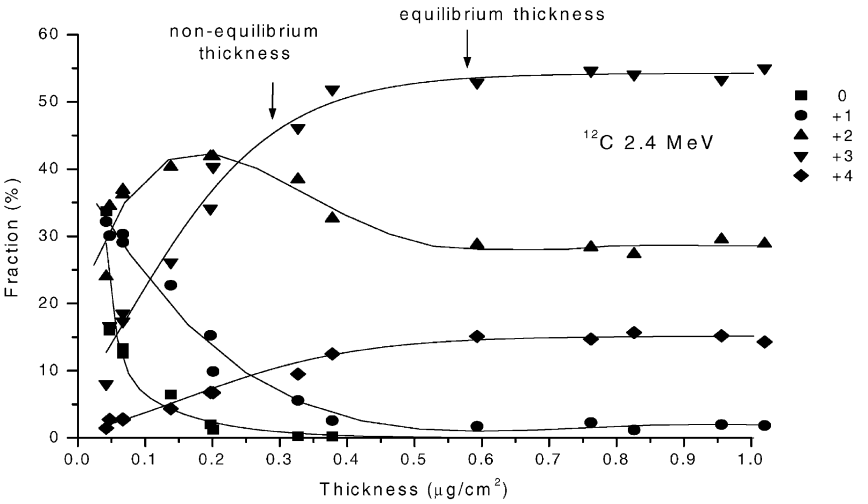

Fig. 3. Charge state distribution as a function of target thickness for ^{12}C ions at a terminal voltage of 2.4 MV. The arrows show the gas thickness where the energy dependence of the charge state distribution has been obtained (presented in Figs. 4 and 6).

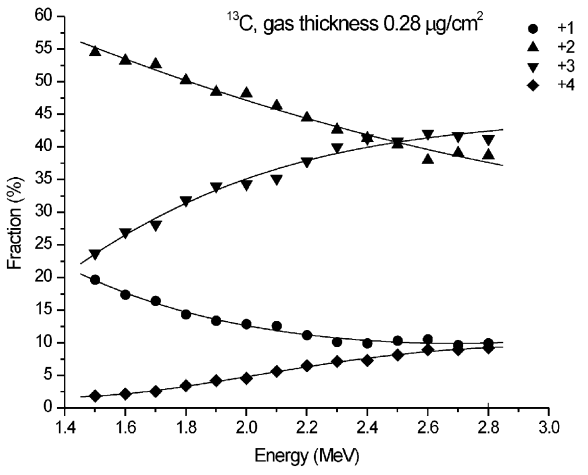

Fig. 4. Charge state distribution for ^{13}C as a function of ion energy at non-equilibrium stripper gas thickness.

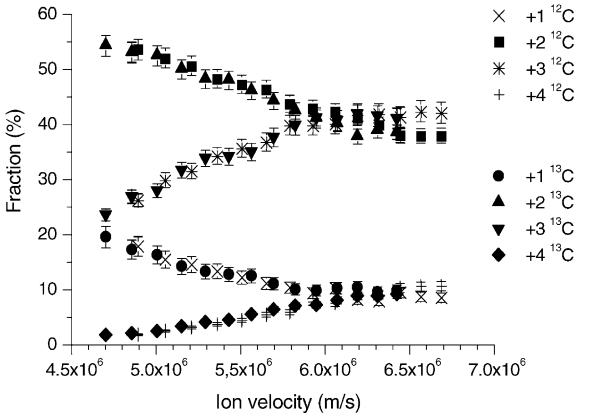

Fig. 5. ^{12}C and ^{13}C charge state distribution as a function of the ion speed at non-equilibrium gas thickness.

be due to fluctuations in the speed of the terminal pumps. According to Ref. [9], at a constant gas inflow into the stripper chamber, the pressure of the stripper gas is a function of the rotational speed of the pumps and this speed could have varied by up to 2.5% during the experiment. Taking into account the results given in Fig. 3, the fluctuation will contribute to a larger extent for charge states $1+$ and $3+$, as these two charge states have the highest gradient in this pressure range.

In Fig. 5 the charge state distributions of both ^{12}C and ^{13}C have been plotted as a function of the ion velocity. The two curves overlap well within the error bars and show, as expected, that to the first approximation the charge distribution for a given stripper medium depends only on the velocity of the ions, specifically for each atomic number. The small difference between the results for the two isotopes seen in the figure may be due

to the fact that the terminal pumps had slightly different speeds in the two cases. This affects the stripper thickness and consequently the charge distribution.

5.3. Equilibrium distribution

The charge state distribution as a function of incident ion energy, at a stripper gas pressure giving approximately equilibrium conditions (see the arrow in Fig. 3) was measured for ^{13}C and is shown in Fig. 6. Charge state 3+ is at its highest concentration of 52% at an energy of about 2.8 MeV and this fraction is greater compared to the non-equilibrium case by approximately 16%. As can be seen, the charge states 1+ and 2+ are more suppressed and the fractions of the charge state for 3+ and 4+ are greater than in Fig. 4.

In Table 1, the mean charge state for ^{13}C ions for various ion energies is given for the gas stripper at equilibrium thickness as well as for a foil stripping. The latter is extracted from Ref. [6]. A comparison of the two cases at a certain ion energy shows that the mean charge is lower in a N_2 gas stripper by as much as 15%.

The statistical error for the various charge state peaks varies depending on the yield. For charge state 3+ it is approximately 1.5%, whereas for charge state 1+ it is as high as 5%. Another error is introduced by the irregularities in the gold foil. Comparing the results from the three different gold foils used at each terminal and gas pressure setting, the total error for the 3+ peak is estimated to be of the order of 2% at equilibrium thickness. The total error for the 2+ and 4+ peaks is estimated to be less than 3.5% and the error in the 1+ peak is less than 6% at equilibrium thickness. However, an additional error caused by the fluctuations in the speed of the terminal pumps will be introduced at non-equilibrium thickness. The contribution of the error is as high as 3% for charge states 1+ and 3+ and is somewhat lower for the other charge states. A fourth error is introduced when the pressure in the stripper gas is calculated on the basis of the measured pressure in the beam tubes outside the tank, and is of the order of 20%. However, this last error will not affect the relative values of the charge states at a certain gas thickness.

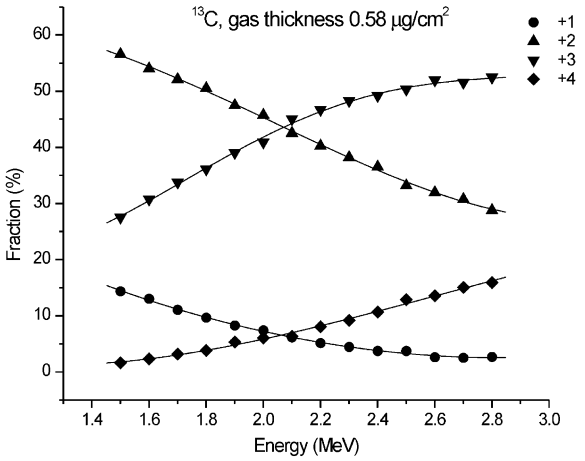

Fig. 6. ^{13}C charge state distribution at equilibrium gas thickness.

Table 1
The mean charge states of ^{13}C in the energy range 1.5–2.8 MeV obtained for gas stripping at equilibrium gas thickness and for foil stripping

Energy (MeV)	Mean charge (gas stripper)	Energy (MeV)	Mean charge (foil stripper)
1.5	2.17		
1.6	2.22		
1.7	2.29	1.725	2.65
1.8	2.34	1.825	2.78
1.9	2.41	1.925	2.80
2.0	2.46	2.025	2.85
2.1	2.51	2.125	2.89
2.2	2.58	2.225	2.92
2.3	2.62	2.325	2.94
2.4	2.67	2.425	3.07
2.5	2.72	2.525	3.06
2.6	2.76	2.625	3.16
2.7	2.79	2.725	3.16
2.8	2.81	2.825	3.22

6. Conclusion

A comparison of results of the gas stripper with results using a foil stripper has been made and is

given in Fig. 2 and in Table 1. For foil stripping ^{13}C charge state 3+ has a maximum at an energy of 2.4 MeV. For gas stripping with N_2 gas, the maximum of ^{13}C charge state 3+ is found to be at about 2.8 MeV. The maximum for ^{14}C cannot be reached at the terminal voltages available with the Pelletron. To minimise the variation in fractionation between ^{13}C and ^{14}C for charge state 3+ in the AMS experiments, an appropriate terminal voltage should be used. This is, however, not attainable with nitrogen gas stripper in the Lund 3 MV Pelletron.

It should be stressed that in AMS experiments the terminal pumping is a major improvement to the system. This is clearly illustrated in Figs. 2b and d, where, with the same gas inlet to the stripper medium, better stripping efficiency has been attained for the gas stripper with terminal pumping. The improved efficiency of the stripper increases the beam transmission through the accelerator. This will open up the usage of the gas stripper for ions that have been impossible to use with a gas stripper earlier. It is especially important for our heavy ion AMS projects, such as the ^{26}Al [13] and ^{59}Ni [14] projects, but could also be useful for the ^{14}C [8] project, as a much more stable stripper medium is obtained. Some first attempts using the gas stripper with terminal pumping in routine ^{14}C measurements have been made. However, equilibrium gas thickness has not been used so far, since the beam has been severely affected by the residual gases in the beam tube, which originate from the stripper system. This will unacceptably increase the beam loss and the divergence of the stripped ion beam.

Possible improvements of the gas stripper could be the use of pipes of a smaller diameter between the pump houses and the accelerator tubes, in order to reduce the cross-sectional area for gas outflow into the accelerator tubes. Such a modification will decrease the number of residual gas molecules in the tubes and therefore increase the transmission. Other possible changes are the use of a different stripper gas, such as Ar, and terminal pumps with a higher pumping capacity. The measurements reported in this paper will in the near future be repeated with Ar as stripper gas and will be extended to other ions of interest for AMS. The installation of terminal pumps with higher pumping capacity would reduce the amount of gas leaking into the accelerator tubes. However, this needs an enlargement of the accelerator terminal, which obviously entails considerable reconstruction work.

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