Equilibrium charge-state distributions of sodium ions in carbon foil

X. Tordoir, T. Bastin *, P.-D. Dumont, H.P. Garnir

Institut de Physique Nucléaire Expérimentale, Université de Liège au Sart Tilman, Bât. B15, B-4000 Liège, Belgium

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Abstract

The equilibrium charge-state distributions have been measured for sodium ions at the exit of a carbon foil for energies ranging from 0.43 to 1.66 MeV. A comparison of our results with available models is performed and an empirical formula for calculating the charge-state fractions of sodium ions is deduced. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The interaction of an ion beam with a solid foil leads to multiple excitation and ionization of the beam ions. If the foil thickness is large enough, the charge-state distribution after the foil reaches an equilibrium [1] which is only dependent, for a given projectile, on the ion velocity and the target material. The knowledge of the equilibrium charge-state distributions is very important when studying beam-foil spectra [2].

In this paper, we report measurements of charge-state distributions of Na ions having interacted with a solid carbon foil. Beam energies in the range 0.43–1.66 MeV have been considered. Since previous measurements were only performed at lower energies [1,3], we extend significantly the knowledge of the Na ions charge-state distributions.

Presently available theoretical descriptions [4,5] are insufficient for predicting accurately the interaction of accelerated ions with a solid foil. Equilibrium charge-state distributions observed for heavy ions having passed through carbon foils were fitted previously using various statistical models, as the gaussian model of Bell [6] or the chi-squared model of Baudinet-Robinet et al. [7]. We have used these two statistical models to fit our results for the Na ions and we present a critical comparison between them.

This paper is organized as follows. In Section 2, the experimental set-up used for our measurements is described. Our results and their interpretation are presented in Section 3. A brief conclusion is given in Section 4.
2. Experiment

A schematic diagram of the experimental set-up is shown in Fig. 1. A sodium ion beam was produced by a 2 MV Van de Graaff accelerator equipped with a radio-frequency (RF) ion source. The principle was to erode by sputtering the exit channel of the ion source covered with an NaCl mixture [8]. Argon was chosen as the buffer gas. After traversing an analyzing magnet, the Na⁺ ion beam passed through a carbon foil thick enough (∼20 μg/cm²) to get equilibrium charge-state distributions. The ion beam was narrowed by use of two 1 mm high × 0.1 mm width rectangular collimators (the first situated before the carbon foil, the second placed 45 cm downstream from the foil, in order to eliminate the particles scattered out of the beam incident direction by the ion-foil interaction). After the second collimator, the ion beam was analyzed with a bending magnet and the ions were detected ≈ 3° off-axis by a passivated implanted planar silicon (PIPS) detector situated at the end of the beam tube. A 200 μm slit was placed in front of the detector. During the measurements the incident beam current was normalized by Rutherford backscattering. A rotating blade (covered with a thin layer of gold) situated before the carbon foil interrupted 400 times per second the ion beam. The backscattered particles were detected with a second PIPS detector.

The charge-state distributions were recorded by varying step by step the value of the magnetic field and counting the corresponding number of particles at the end of the beam tube. A typical charge-state spectrum is shown in Fig. 2. The charge-state fractions \( F(q) \) were deduced from the charge-state spectrum by the ratio of the various peak amplitudes to the sum of these amplitudes. The neutral ions could not be measured, as they were not deflected by the bending magnet and therefore not detected. We assumed the number of neutral ions was negligible as it was measured to be 0.2% of the total number of ions at 0.4 MeV by Lennard et al. [1] and it decreases when the energy is increased.

3. Results and discussion

Charge-state fractions \( F(q) \) have been measured for various beam energies ranging between 0.5 and 1.8 MeV. Energy loss inside the foil has been deduced from the measurement of the beam energy after the foil by use of the bending magnet after the excitation chamber. The range 0.5–1.8 MeV before the foil corresponded to the range 0.43–1.66 MeV after the foil. Energy values are estimated to be accurate with an uncertainty of 3%. For each energy, the experimental mean charge

\[
\bar{q} = \sum_q F(q)q
\]

and distribution width

\[
d = \sqrt{\sum_q F(q)(q - \bar{q})^2}
\]

have been computed and are represented respectively, in Figs. 3 and 4, with respect to the ion
beam energy after the foil. In these figures, previous results of Lennard et al. [1] and Hvelplund et al. [3] have also been plotted. We immediately see that our results are in a good continuity with previous ones.

3.1. Mean charge

Various semiempirical or empirical formulas for $\bar{q}$ of rapid ions interacting with carbon foils have been proposed in the past (see e.g. [9]). Each

Fig. 2. Charge-state spectrum for a 1.5 MeV Na beam.

Fig. 3. Mean charge $\bar{q}$ versus ion energy after the foil. Points represent experimental data, while the solid line is a fitted curve (see text). Experimental data are from this work (■), Lennard et al. [1] (+) and Hvelplund et al. [3] (×). Error bars represent twice the standard deviation of our measurements.
of them is only valid within their limited domain of derivation. In our case, we used, to get a fitting curve of all available experimental data, the formula given in [9]

\[ \tilde{q} = Z \left[ 1 - \exp \left( - \sum_i a_i X^i \right) \right], \quad (3) \]

where \( Z \) is the atomic number, \( a_i \) are constants and \( X \) is the reduced atomic velocity connected to the atomic velocity \( v \) by

\[ X = \frac{v}{v'} Z^{-0.45} \quad (4) \]

with \( v' = 3.6 \times 10^8 \) cm/s.

A good fit has been obtained by limiting the sum in Eq. (3) to the first two terms, giving the results \( a_1 = 0.96 \pm 0.03 \) and \( a_2 = 1.05 \pm 0.13 \). The fitted curve is represented by a solid line in Fig. 3.

3.2. Distribution width

For describing charge-state distribution width of ions passing through carbon foils, there exist also several semiempirical or empirical formulas. We have used the following function:

\[ d = b_1 \tilde{q}^{b_2} \left( 1 - \frac{\tilde{q}}{Z} \right)^{b_3} \quad (5) \]

where \( \tilde{q} \approx Z \)

which is very similar to those given by Nikolaev and Dmitriev [10] and by Betz [5].

The fit, represented in Fig. 4 by a solid line, yields \( b_1 = 0.75 \pm 0.01 \), \( b_2 = 0.53 \pm 0.07 \) and \( b_3 = 1.2 \pm 0.2 \).

3.3. Charge-state fractions

The charge-state fractions with respect to the ion beam energy after the foil are shown in Figs. 5–7 for the Na I to Na VII ions. In these figures, the points represent experimental data, while the solid and dashed lines are values calculated respectively from a gaussian and a chi-squared model.

In the gaussian model (see e.g. [11]), the charge-state fraction is written

\[ F(q) = \frac{1}{\sqrt{2\pi d^2}} \exp \left( - \frac{(q - \tilde{q})^2}{2d^2} \right) \quad (6) \]

and in the chi-squared model [7],

![Figure 4. Charge distribution width \( d \) versus ion energy after the foil. Points represent experimental data, while the solid line is a fitted curve (see text). Experimental data are from this work (■), Lennard et al. [1] (+) and Hvelplund et al. [3] (×). Error bars represent twice the standard deviation of our measurements.](image-url)
$F(q) = \frac{c^{\nu/2}}{2^{\nu/2} \Gamma(\nu/2)} (q + 2)^{\nu/2 - 1} \exp \left( -\frac{c(q + 2)}{2} \right)$,

\[ c = \frac{2(\bar{q} + 2)}{d^2}, \quad \nu = \frac{2(\bar{q} + 2)^2}{d^2}. \]

where \( c \) and \( \nu \) are related to the mean charge \( \bar{q} \) and the distribution width \( d \) by the formulas.

Solid and dashed lines of Figs. 5–7 have been computed on the basis of Eqs. (6) and (7) using the fitted functions (3) and (5) for \( \bar{q} \) and \( d \), respectively. Let us mention that all these curves depend...
only on the same five parameters $a_1, a_2, b_1, b_2$ and $b_3$.

From Figs. 5–7, one sees clearly that the chi-squared model best fits the data for projectile energies below 0.4 MeV. Inversely, above 0.5 MeV, the gaussian model yields better results. This is not a surprise, as the charge-state distributions at low energies are known to be asymmetric [7]. This asymmetry is not reproducible by use of gaussian distributions.

4. Conclusions

The equilibrium charge-state distributions have been measured for sodium ions at the exit of a carbon foil for energies ranging from 0.43 to 1.66 MeV. We have extended significantly the knowledge of the charge-state distributions of these ions, as previous experimental results were only available at lower energies [1,3]. Empirical formulas for calculating the charge-state distribution mean and width have been proposed. These formulas are valid in the domain of all experimental data available so far (0.09–1.66 MeV). Finally, the charge-state fractions have been compared with the gaussian and the chi-squared model of Bell [6] and Baudinet-Robinet et al. [7], respectively.

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References