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Equilibrium charge state distributions for boron and carbon ions emerging from carbon and aluminum targets

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ABSTRACT

Equilibrium charge state distributions of boron and carbon ions through carbon and aluminum targets were measured with an energy range of 3–6 MeV. Comparisons of the data with relevant semi-empirical models for the equilibrium mean charge states and for the charge state distribution widths could provide valuable insight on the underlying mechanisms for a fast ion to lose or capture electrons. In-depth examinations of the experimental results in combination with semi-empirical models suggest that equilibrium charge state distributions are well represented by Gaussian distributions.

1. Introduction

Fast ions lose energy by Coulombic interactions with the electrons of a medium so knowledge of the charge state of the ion is essential to describing a number of fundamental properties including the stopping power of the medium and the range of the ions [1]. Radiation effects and dosimetry are two of many areas that are ultimately dependent on the charge state of the incident ion. Applications of importance range from accelerator design and accelerator mass spectrometry to medical therapy. Unfortunately, significant gaps exist in the data for the charge state distribution of low-energy ions in solid materials, which makes it difficult to determine the trustworthiness of stopping power and range compilations.

Significant amounts of data exist on equilibrium charge states for ions of low atomic number, Z, in carbon targets. This information can be found in several reviews [2–6]. Such systematic data does not exist for many other targets, which is the case with aluminum. The few studies on the equilibrium charge states of low Z ions in aluminum have explored energy in the keV range and sporadic energy increments between 10 and 100 MeV [4]. Aluminum is a typical lightweight target material that is used extensively for windows. The much needed information on equilibrium charge states of ions often has to be extrapolated and there is not enough confidence in the models that such a procedure can be performed reliably.

In this work, equilibrium charge state distribution measurements have been performed for boron[1] and carbon ions emerging from carbon and aluminum foils in the energy range of 3–6 MeV. The present data is compared to the predictions of relevant semi-empirical formalisms provided by Schiwietz et al. and Ziegler–Biersack-Littmark based on their inclusion of target dependence terms [7–9]. In addition, the Gaussian behavior of the charge state fractions is explored and charge state distribution widths are evaluated and discussed.

2. Experimental procedure

The experimental procedures have been discussed in a previous paper, but will be briefly described below [10]. Boron and carbon ions are produced by a Source of Negative Ions by Cesium Sputtering negative-ion source, SNICS, and accelerated by the FN Tandem Van de Graaff in the Nuclear Structure Laboratory at the University of Notre Dame. The incident ions pass through the accelerator mass spectrometry (AMS) beamline and through target foils in a target chamber. Some of the ion beam is Rutherford scattered into a silicon (monitor) detector located in the target chamber, which acts as an ion beam monitor and a normalization tool. The un-scattered beam is sent directly into a Browne–Buechner Spectrograph where the charge state fractions are separated magnetically and mea-

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1 ^{10}B was used and then scaled to ^{11}B to compare with established data.

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sured by an electron suppressed Faraday cup. This experimental procedure is repeated as a function of energy for each ion and target combination.

When a charge state distribution for a given energy has been measured, the charge fractions, F_q, can be calculated using $F_q = N_q/\Sigma N_q$, where N_q is given by $N_q = I_q/qeW$ with I_q being the current read from the Faraday cup for a specific charge state q, e is $1.6 \times 10^{-19} C$ and W is the normalization counts from the monitor. Following the determination of the charge fractions, the mean charge can be determined using $\bar{q} = \sum qF_q$ and the distribution width, $d = [\sum (q-\bar{q})^2 F_q]^{\frac{1}{2}}$, can also be calculated. This procedure was applied to both carbon and boron ions in carbon and aluminum targets and the experimental results are summarized in Table 1. Charge equilibrium is reached when sufficient collisions have occurred and the electron loss rate equals the electron capture rate. The attainment of equilibrium is based on previously reported experimental results or determined from charge state fraction measurements for several targets of different thicknesses [4,5,11]. The charge state fractions will remain constant for sufficiently thick targets, provided significant energy loss by the incident ions does not occur. Both the carbon and aluminum target had a thickness of $\sim$20 µg cm^{-2} as confirmed by energy loss measurements with an alpha particle source.

3. Results and discussion

3.1. Comparison with empirical models for mean charge states

A variety of semi-empirical models have been developed to predict the experimental mean charge states. These models were usually constructed from data for a limited number of ions and targets and were optimized over a finite energy range. Effective charge can be obtained from stopping powers and does not always correspond to the mean charge state. The following formulae for mean charge states are examined in more detail since they are valid for the energy range covered in this work and they allow for target dependence in their formalism. In both models, the relative ionization ($\bar{q}/Z$) is given. This quantity is defined as the mean charge state of the ion divided by its Z.

A formula created by Schiwietz et al. [8] uses a highly parameterized least-square fit built from an array of over 800 data points that span a wide variety of ions and targets. The expression for the relative ionization is given as

$$\bar{q} = Z\left[\frac{(8.29x + x^4)}{0.06/x + 4 + 7.4x + x^4}\right], \quad (1)$$

where

$$x = c_1(\tilde{v}/c_2/1.54)^{1+1.83/Z}, \quad (2)$$

is a reformulated reduced velocity and the power term is used to adjust the steepness of the charge state response as a function of x with the following correction terms:

$$c_1 = 1 - 0.26\exp(-Z_t/11)\exp(-(Z_t - Z)^2/9) \quad \text{and}$$
$$c_2 = 1 + 0.030\tilde{v}\ln(Z_t). \quad (3)$$

The first term in Eq. (3) accounts for resonant electron capture, which reduces the mean charge state or similarly x for symmetrical ion-target combinations, while the second correction term allows for a target dependent deformation at high velocities. The final component in the reformulated reduced velocity is the scaled projectile velocity

$$\tilde{v} = Z^{-0.543} v_p/v_B. \quad (4)$$

The sub- and superscripts have "p" for projectile, "B" for Bohr and "t" for target. The limitation noted for this model is that the ratio of the projectile velocity to the Bohr velocity must be >0.4 for $Z \geqslant 3$.

The second relative ionization expression to be examined here is from the Ziegler–Biersack–Littmark model that is used in the well known SRIM and TRIM codes [9]. For ions of $Z > 2$ the Ziegler, Biersack and Littmark formula can be written as:

$$\bar{q} = Z\left[1 - \exp(0.803y_r^{0.3} - 1.3167y_r^{0.6} - 0.381557y_r - 0.008983y_r^3)\right], \quad (5)$$

where y_r is the reduced velocity as given by $v_r/v_B Z^{2/3}$ and v_r is the relative velocity as given by

$$v_r = v(1 + v_F^2/5v^2), \quad (6a)$$

for $v > v_F$ and

$$v_r = 3v_F/4(1 + 2v^2/3v_F^2 - v^4/15v_F^4), \quad (6b)$$

for $v \leqslant v_F$ where v is ion velocity and v_F is the Fermi velocity of the medium.

An examination of the relative ionization as a function of energy can be used to compare predictions of the Schiwietz model with

Table 1
Experimental charge fractions, mean charges, distribution widths and skewness for carbon and boron ions in carbon and aluminum targets.

$^{11}B^{2+}$	Incident Energy (MeV)	$\bar{q}$	d	s	2+	3+	4+	5+	
$Z_2 = 6$	5.5	3.73	0.64	0.19	0.46	36.6	52.85	10.09	
	6.05	3.83	0.64	0.06	0.41	29.42	57.32	12.84	
	6.6	3.89	0.65	−0.08	0.94	23.98	59.98	15.26	
$Z_2 = 13$	3.3	3.24	0.65	0.14	9.99	57.78	30.32	1.9	
	4.4	3.56	0.67	0.004	4	42.81	46.88	6.31	
	5.5	3.73	0.68	0.02	1.99	34.43	52.17	11.41	
	6.05	3.84	0.68	−0.06	1.38	28.09	55.68	14.86	
$^{12}C^{2+}$	Incident energy (MeV)	$\bar{q}$	d	s	2+	3+	4+	5+	6+
$Z_2 = 6$	3	3.39	0.65	0.03	6.19	51.63	39.38	2.8	0
	4	3.78	0.63	−0.12	1.55	28.64	60.3	9.36	0.15
	5	3.96	0.58	0.06	0.66	16.36	70.38	11.73	.87
	5.5	4.09	0.63	0.07	0.46	13.67	63.65	21.13	1.11
	6	4.18	0.63	0.24	0	10.47	62.12	25.87	1.54
$Z_2 = 13$	3	3.46	0.69	−0.12	7	43.8	45.1	4.1	0
	4	3.87	0.68	−0.01	1.32	26.21	56.77	15.37	0.35
	5	4.04	0.66	0.33	0.59	15.31	65.57	16.22	2.31
	5.5	4.18	0.67	0.07	0.34	12.45	58.26	27.01	1.94
	6	4.27	0.68	0.23	0	10.03	55.9	30.79	3.28