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Direct Observation of Energy Loss of Charge-Frozen Hydrogen-Like Ar Ions

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Abstract

We measured the energy loss of charge-frozen clothed ions (i.e., partially stripped ions which maintain their charge states throughout the passage) in a Si solid employing a totally depleted silicon detector with 4.1 μm thickness as a target, to measure the energy deposition of 390 MeV/u Ar^{17+} directly. Under the present conditions, the probability of the electron loss is not so large, and that of the electron capture is negligibly small. Accordingly, the energy loss of charge-frozen Ar^{17+} ions in a rather thick target can be measured. Charge states of ions transmitted through the target were observed by a 2D-position sensitive detector in coincidence with the energy deposition. We have obtained an effective charge of Ar^{17+} ions for the stopping power, as $Z_{\mathrm{eff}} = 17.36$ (±0.03).

1. Introduction

Extensive studies on the stopping power (i.e., energy loss) of partially stripped ions have been performed so far. Effects of screening by bound electrons or charge exchange processes have been experimentally investigated using gas or solid targets [1,2]. However, energy loss measurements of partially stripped ions with fixed charge state are restricted because of the large probability of charge exchange. Datz *et al.* have measured the energy loss of 2 MeV/u ions of $Z = 1$ to 9 which have not changed their charge state under Au $\{111\}$ planar channeling [3]. In a random incident condition, a stopping power of 32 MeV (~10.7 MeV/u) $^3He^{1+}$ was measured by Ogawa *et al.* [4]. Theoretically, Kim and Cheng extended the Bethe formula [5] for partially stripped ions by considering the electronic structure of the projectile as well as the target atom, and introduced a formula where the projectile charge, Z_p, and the target mean ionization energy, I, are replaced with the effective charge, Z_{eff}, and the effective mean ionization energy, I_{eff}, respectively [6]. On the basis of Bethe theory, Kaneko derived an analytical formula for hydrogen-like and helium-like ions ignoring the projectile excitation process [7], and Cabrera-Trujillo *et al.* also gave an analytical formula which consists of two parts originating in the electronic structures of the projectile and the target atom, and considering the projectile excitation and velocity dependent number of bound electrons [8].

We have measured the energy loss (to be exact, energy deposition to the target) of 390 MeV/u Ar^{17+} ions in a Si target with. 4.1 μm thickness, which is comparable to the mean free path for ionization of Ar^{17+} [9]. Electron capture processes can be disregarded for Ar ions in such a high energy region. Therefore, a condition for partially stripped ions to maintain their incident charge state has been perfectly achieved under the present experimental conditions. For relativistic heavy ions higher than several 100 MeV/u, the Mott cross section [10] should be adopted for calculating the stopping power and energy straggling. Deviations from the results of the first order Born approximation have been observed [11,12]. Moreover, the energy deposition is smaller than the energy loss by ~15 percent due to the escape of binary encounter electrons from the target in the present energy region, which was evaluated by a Monte Carlo simulation.

2. Experiment

390 MeV/u Ar^{17+} or Ar^{18+} ions with an angular divergence less than 0.15 mrad were injected into a 4.1 μm Si target, a totally depleted silicon detector for measuring the energy deposition. The energy resolution, σ_0, was 140 keV. The transmitted ions through the target were charge-separated by a 0.5 T magnet, and detected by a 2D-position sensitive detector in coincidence with the energy deposition. The target detector is covered with 40 $\mu g/cm^2$ Au at the entrance side and 20 $\mu g/cm^2$ Al at the exit side. We can neglect the energy loss in the Au region, which is estimated to be a fraction of 10^{-6} of the incident energy.

3. Result and discussion

The survival fraction of 390 MeV/u Ar^{17+} ions transmitted through the 4.1 μm Si target was 25 percent. The energy deposition spectra for Ar^{18+} and Ar^{17+} which maintained their incident charges throughout the passsage, are shown in Fig. 1. The ratio $\Delta E_d(17)/\Delta E_d(18)$ amounts to 0.917. $\Delta E_d(18)$ and $\Delta E_d(17)$ are the mean energy deposition for Ar^{18+} and Ar^{17+}, respectively.

A Monte Carlo simulation for 390 MeV/u Ar^{18+} was performed to evaluate the effect of the escaped electrons and the width of the experimental spectrum. The detailed procedure of the simulation is explained elsewhere [13]. The distant collision component, with an impact parameter larger than the Thomas-Fermi radius, was calculated analytically. A reasonable energy width of the spectrum can be obtained simulating only the close collision component by the Monte Carlo method, because the energy straggling is mainly originating from close collisions. The Mott cross section expanded to the first order of $(Z_p e^2/\hbar v)$ was adopted as the collision cross section, where e is the electron charge,

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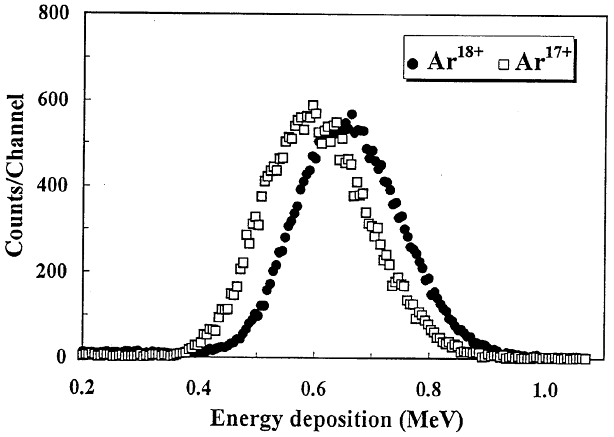

Fig. 1. Experimental energy deposition spectra for 390 MeV/u Ar^{18+} ions (closed circle) and Ar^{17+} ions (open square) through 4.1 μm Si.

Table I. *Stopping powers of hydrogen-like Ar ions obtained from the present experiment and calculations by formulas in Ref. [7] and Ref. [8] (projectile electron number is fixed as* $\mathrm{N}_I = 1$*), and stopping powers of bare Ar ions obtained from the present simulation and calculations by non-relativistic and relativistic (with* Z_p^3 *term of the Mott correction) Bethe formulas.*

Hydrogen-like Ar	(MeV/cm)
The present experiment	1790
Calculation [7]	1703
Calculation [8]	1670
Bare Ar	**(MeV/cm)**
The present simulation	1926
Calculation (R.B.)	1926
Calculation (NR.B.)	1848

$\hbar$ is Planck's constant, and v is the projectile velocity [14]. The simulated results are shown in Fig. 2. The FWHM of the energy deposition distribution, σ_1, is evaluated to be 110 keV, and $\sqrt{\sigma_0^2 + \sigma_1^2}$, is 180 keV, which is close to the experimental value of 190 keV (see in Fig. 1). The mean energy loss, $\Delta E_{\mathrm{l}}^{(\mathrm{s})}(18)$, and the mean energy deposition, $\Delta E_{\mathrm{d}}^{(\mathrm{s})}(18)$, for Ar^{18+} injection are 0.790 and 0.661 MeV, respectively. The mean energy of the escaped electrons, E_{es}, is given by the average of the difference between these two spectra. The value of E_{es} for Ar^{17+} can be regarded as the same as that for Ar^{18+}. Therefore, the energy loss ratio of Ar^{17+} to Ar^{18+} is given by

$$\frac{\Delta E_{\mathrm{l}}(17)}{\Delta E_{\mathrm{l}}(18)} = \frac{\Delta E_{\mathrm{d}}(17) + E_{\mathrm{es}}}{\Delta E_{\mathrm{d}}(18) + E_{\mathrm{es}}}. \tag{1}$$

Absolute values of energy deposition of Ar^{18+} have been measured for 19.4, 31.5, 78.5 and 94.7 μm targets, and our simulations agree with the experimental results within ~6 percent. Assuming that the experimental $\Delta E_{\mathrm{d}}(18)$ is the same as the simulated $\Delta E_{\mathrm{d}}^{(\mathrm{s})}(18)$, $\Delta E_{\mathrm{d}}(17)$ and $\Delta E_{\mathrm{l}}(17)$ are evaluated to be 0.606 and 0.735 MeV, respectively. Accordingly, $\Delta E_{\mathrm{l}}(17)/\Delta E_{\mathrm{l}}(18)$ was obtained to be 0.930.

It is worth to note that survived Ar^{17+} ions have a possibility of having passed through where the electron density is small. However, it is considered to be a rare process in the case of a 4.1 μm target, and the electron density along the trajectory of all Ar ions can be represented by the mean electron density of the target. Under the present conditions, the Z_{p}^3 term of the Mott correction is at most 2 percent of the Bethe stopping power, which is proportional to Z_{p}^2, and the effective charge can be evaluated by the formula $Z_{\mathrm{eff}} = Z_{\mathrm{p}}[\Delta E_{\mathrm{l}}(17)/\Delta E_{\mathrm{l}}(18)]^{1/2}$. As a result, Z_{eff} has been obtained to be 17.36 ($\pm$0.03), and the screening effect by a bound electron, η, defined as $\eta = (Z_{\mathrm{p}} - Z_{\mathrm{eff}})/N_{\mathrm{e}}$, is 0.64, where N_{e} is the number of bound electrons.

For the case of 2 MeV/u ions of $Z = 1$ to 9 under the planar channeling condition, η was found to be 0.9 [3]. Such strong screening may be due to a reduction of close collisions for channeling ions. For the random incident case of 32 MeV $^3\mathrm{He}^{1+}$ ions in a carbon target, the screening effect is reported to be 0.54 [4], which is slightly smaller than our result. This feature can be understood as follows. The orbital radii of 1s electrons of He and Ar, $\langle r\rangle_{\mathrm{He}}$ and $\langle r\rangle_{\mathrm{Ar}}$, are 0.40 and 0.044 Å, respectively. The effect of excited states is not so significant, since the occupation probability of excited states is at most 10 percent for both cases [9]. The contributions from distant collisions with impact parameters larger than $\langle r\rangle_{\mathrm{He}}$ and $\langle r\rangle_{\mathrm{Ar}}$ are estimated to be 40 and 65 percent of the total stopping powers for 32 MeV bare $^3\mathrm{He}^{1+}$ in carbon and 390 MeV/u bare Ar^{18+} in silicon, respectively. The larger screening of $\eta = 0.65$ is considered to reflect the larger contribution from distant collisions. η may be modified for a thicker target due to excited electrons.

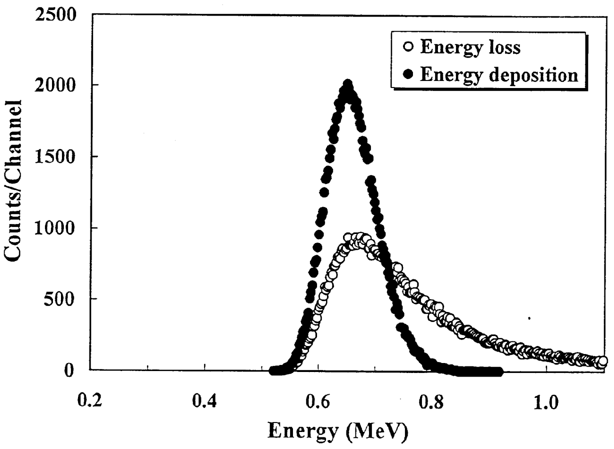

Fig. 2. Simulated spectra of energy loss (open circle) and energy deposition (closed circle) for 390 MeV/u Ar^{18+} ions through 4.1 μm Si.

The stopping powers of hydrogen-like and bare Ar ions obtained by the present experiment and simulation together with results calculated by means of several theoretical formulas, are listed in Table I. The calculated results for hydrogen-like Ar are 5~7 percent smaller than the present experimental result. Formulas adopted for calculation in Ref. [7] and Ref. [8] are non-relativistic. For bare Ar ions, the non-relativistic Bethe result is 4 percent smaller than the result of the relativistic Bethe formula with a Z_{p}^3 term from the Mott correction. Therefore, the 5~7 percent deviation for hydrogen-like Ar can be attributed to the lack of relativistic correction in the theories. In this sense, the present result is in good agreement with theoretical predictions.

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