Measurements of energy losses of 10-MeV neutral hydrogen atoms in carbon foils

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Mean energy losses of 10.4-MeV neutral hydrogen atoms penetrated through thin carbon foils of 3.7–13.4 $\mu g/cm^2$ were measured using a high-resolution magnetic spectrograph. The measured particles are those entered into the carbon foil as H^0 and emerged from it as H^0. From the attenuation measurement of H^0 in the foils, we can regard the energy losses as those of H^0 in a frozen charge state. The measured stopping power of carbon for 10.4-MeV H^0 is 21.3 ± 1.8 eV/($\mu g/cm^2$) and is about one-half that for H^+ at the same speed. This result agrees well with the theoretical predictions based on the first-order Born approximation. [S1050-2947(96)11709-1]

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I. INTRODUCTION

In order to improve the understanding of the stopping processes of fast ions in solids, the energy losses in individual charge states and the charge-changing cross sections are the essential quantities to be investigated. Here we consider a fast proton as a projectile, since only a couple of charge states, i.e., bare and neutral, are involved. The charge states in solids can be described by electron capture into and subsequent electron loss from bound states on the proton [1]. Furthermore, the equilibrium charge states emerging from the solid and the approach to equilibrium of particles at sufficiently high speeds within the solid can be presented with the loss and capture cross sections in the gas. This idea is confirmed by the measurements with solid carbon and gaseous compounds [2–4]. Thus the charge states of fast protons in solids have been investigated vigorously.

On the other hand, the energy-loss measurement of neutral hydrogens is practically difficult, because it is very small compared to the incident energy due to the shortness of the mean free path. Indeed, the measurement of fixed-charge stopping power for H^0 has been reported only in the H_2 gas at the energy range of 40–460 keV [5–7]. No experimental data with solid targets have been reported, to the best of our knowledge.

This paper reports on measurements of the fixed-charge stopping powers of carbon for 10-MeV neutral hydrogen atoms using a high-resolution magnetic spectrograph. The obtained fixed-charge stopping power is compared with the theoretical prediction based on the first-order Born approximation.

II. EXPERIMENT

The H^+ beams were accelerated and extracted from the AVF cyclotron at Research Center for Nuclear Physics, Osaka University. Two sets of a single quadrupole and a 90° dipole magnet in the beam transport system form a beam monochrometer system. The calibrated energy of the H^+ beams was 10.41 ± 0.01 MeV. This corresponds to the speed of $20.4 v_0$, where v_0 is the Bohr velocity.

A schematic diagram of the experimental arrangement is shown in Fig. 1. The momentum-analyzed beams were transported to the first carbon foil, where H^0 atoms were produced

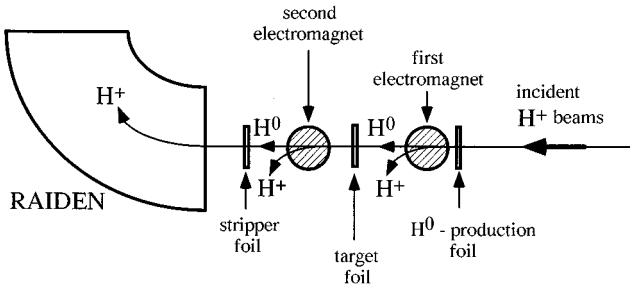

FIG. 1. Schematic diagram of the experimental arrangement.

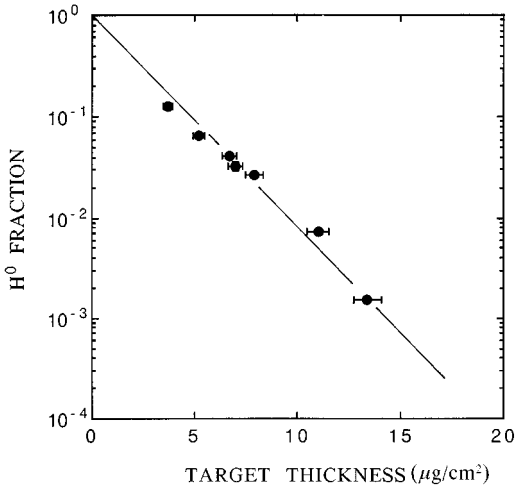

FIG. 2. The fractions of 10.4-MeV H^0 beams penetrated through carbon foils as a function of the foil thickness. The solid curve represents a least-squares fitting with Eq. (1).

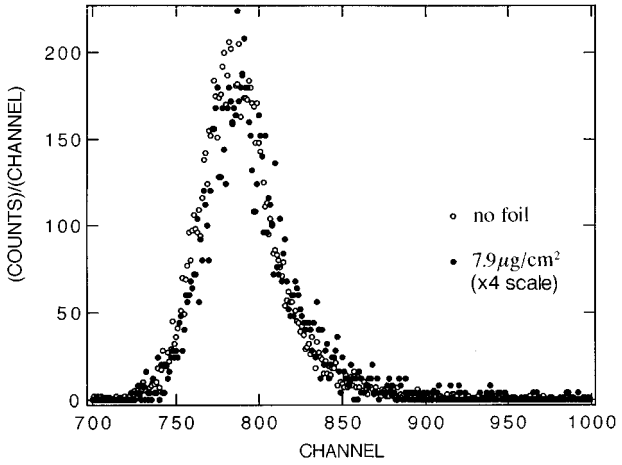

FIG. 3. Typical energy spectrum of 10.4-MeV H^0 traversing a carbon foil of 7.9 μg/cm^2 and that with no target foil. A higher channel on the abscissa corresponds to a larger energy loss. One channel is equivalent to about 41 eV. The spectrum with the target foil is plotted with $\times 4$ scale.

by the electron-capture collisions with carbon atoms. The thickness of this foil was 5.2 μg/cm^2; thus, only $\sim 10^{-6}$ of the initial H^+ beams was neutralized and impinged on the target foil. The residual H^+ ions were swept away from the beam line by the first electromagnet. The thickness of the target carbon foils ranged from 3.7 μg/cm^2 to 13.4 μg/cm^2, which was determined by the Rutherford backscattering method with 2-MeV alpha beams of the 1.7-MV Tandem Van de Graaff accelerator at Nara Women's University. The uncertainty of the foil thickness was estimated to be $\pm 5\%$.

Since the H^+ ions which lost the electron in the target foil were removed by the second electromagnet, only the surviving H^0 atoms were led to a carbon stripper foil of 6.7 μg/cm^2 placed at the center of the scattering chamber. In this foil, more than 95% of the incident H^0 was converted to H^+. Although the pressure around the target foils was about 5×10^{-6} Torr, no thickening of the foils due to beam irradiation was observed.

The H^+ ions emerging from the stripper foil were momentum-analyzed with a high-resolution magnetic spectrograph RAIDEN [8], and were detected by a position-sensitive proportional counter followed by a plastic scintillation counter. Details of the beam-line layout and the counter system have been described elsewhere [9].

In order to study the contribution from charge-changing collisions, the attenuation of H^0 beams in carbon foils was measured as a function of foil thickness. This measurement was carried out with all of the target foils used in the energy-loss measurement. Figure 2 represents the results. The experimental errors of the measured H^0 fractions were within $\pm 5\%$ and smaller than the size of the symbols in the figure. When the foil is thin enough to neglect the contribution from the electron-loss and subsequent electron-capture collisions, the attenuation of H^0 beams in a foil of thickness t can be given as

$$F_0(t) = \exp(-\sigma_l t), \tag{1}$$

where σ_l denotes the electron-loss cross section of H^0. A solid line in the figure represents the least-squares fitting with Eq. (1). As is clear from the figure, the dependence of the attenuation on the foil thickness closely follows an exponentially decaying line. Therefore, the contribution from even a single cycle of the electron-loss and subsequent electron-capture collisions is negligibly small in the thickness of our carbon foils. From the fitting, σ_l was determined to be $(9.75\pm 0.68)\times 10^{-18}$ cm^2. The associated error contains the goodness of the fitting and the errors of the foil thickness. From a theoretical calculation based on the Born approximation by Gillespie [10], the electron-loss cross section of 10.4-MeV H^0 in the ground state by carbon is estimated to be 8.56×10^{-18} cm^2. This value roughly agrees with our data.

Here we briefly mention the effect of the $2S$ metastable state of H^0 atoms produced in the first foil. As discussed in our previous paper [11], the electron-loss cross section of H^0 in the $2S$ state is about four times larger than that of the ground-state atom. If the contribution from the $2S$ state were not negligible, the attenuation of H^0 would be expressed by a superposition of two exponential decay curves with different decay rates. As mentioned above, however, the data can be fitted well with a single exponential. Therefore, there was no sizable fraction of the $2S$ state in the H^0 beam.

Before and after the measurements of the energy losses in each target foil, the target was removed from the beam position and the energy of the incident H^0 beams was monitored directly. A typical energy spectrum of the energy-analyzed H^+ ions that have traversed a target foil of 7.9 μg/cm^2 is presented in Fig. 3, together with that for the incident H^0 beams produced in the first foil. Since the total intensity of the spectrum with the target foil was much smaller than that of the incident H^0 beams, the spectrum with the target foil is shown with $\times 4$ scale. The energy-loss measurements were carried out five times for each target foil. The mean energy loss was determined from the difference between the first moments of the energy-loss spectra with and without a target foil.

For all of the target foils used in the present measurement, a single peak appeared, and its position shifted to the larger energy-loss side (higher channel number) as the foil thick-

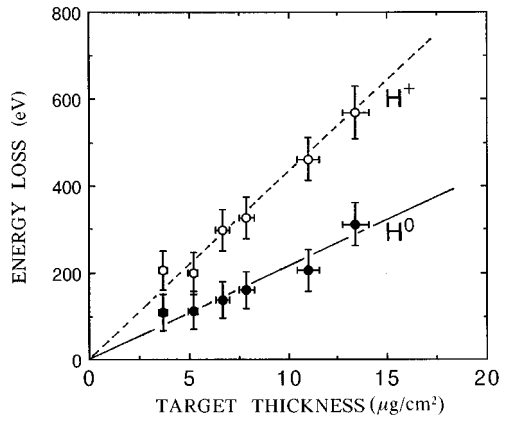

FIG. 4. Foil-thickness dependence of the energy loss for 10.4-MeV H^0 (solid circles) and 10.2-MeV H^+ (open circles). Solid and dashed lines give the least-squares fitting to H^0 and H^+ data, respectively.

ness increased. A double-peak structure, which was observed in our previous measurements with $^3He^+$ and $^6Li^{2+}$ ions [12,13], was not observed. This is consistent with the result of the attenuation measurement and certifies that the contribution from even a single cycle of the electron-loss and subsequent electron-capture collisions is negligibly small.

For further verification of the correctness of our experiments, an energy-loss measurement of H^+ was also carried out with the same target foils. In this measurement, both of the electromagnets were kept off and the first and third carbon foils were removed from the beam line. Owing to the fine adjustment of the beam handling system, the incident energy at this measurement differed slightly from that for H^0. The calibrated energy of H^+ ions impinging on the target was 10.23 ± 0.01 MeV.

III. RESULTS AND DISCUSSION

Figure 4 represents the foil-thickness dependence of the energy loss. The solid and dashed lines in the figure show the least-squares fittings to the data for H^0 and H^+, respectively. From the tangent of the solid line, the stopping power of carbon for 10.4-MeV H^0 was determined to be 21.3 ± 1.8 eV/(μg/cm^2). The associated errors were estimated by taking account of the goodness of the fitting and the errors of the foil thickness. As mentioned above, we can regard this value as the fixed-charge stopping power for the ground-state H^0 atom.

Similarly, the stopping power for 10.2-MeV H^+ was determined to be 42.6 ± 3.1 eV/(μg/cm^2), in agreement with 40.0 eV/(μg/cm^2) given in the compilation by Andersen and Ziegler [14]. In order to compare the stopping power for H^0 with that for H^+ at the same energy, the stopping power for 10.4-MeV H^+ was reduced by scaling the present value at 10.2-MeV with the compilation by Andersen and Ziegler (AZ) [14] as

$$S_p(10.4)=S_p(10.2)\,\frac{S_{\mathrm{AZ}}(10.4)}{S_{\mathrm{AZ}}(10.2)}, \tag{2}$$

where $S_p(x)$ and $S_{\mathrm{AZ}}(x)$ are the experimental data and the compilation value by Andersen and Ziegler at x-MeV, respectively. As a result, the stopping power of carbon for 10.4-MeV H^+ was determined to be 42.1 ± 3.1 eV/(μg/cm^2). Additionally, from the precise stopping power measurement of carbon for 4–13 MeV protons by Sakamoto, Ogawa, and Shiomi-Tsuda [15], the stopping power was interpolated to be 39.5 eV/(μg/cm^2). The present value also agrees with their data.

The stopping power for H^0 is about half of that for H^+. This reduction is qualitatively explained by the screening effect of the electron bound to the projectile. The effective charge for H^0, which reflects the degree of screening by the bound projectile electron, is defined as

$$Z_{\mathrm{H,screen}}=Z_1\times(S_{\mathrm{H}}/S_p)^{1/2}, \tag{3}$$

where S_{H} and S_p are the stopping powers for H^0 and H^+, respectively. Z_1 denotes the projectile nuclear charge. Substituting the present data in Eq. (3), we obtained 0.71 ± 0.04 for the effective charge of H^0. The screening per electron, which is defined as $(Z_1-Z_{\mathrm{H,screen}})$, is 0.29 ± 0.04. The corresponding value for He^+ obtained in our previous measurement is 0.54 ± 0.07 [12]. This difference is qualitatively reasonable because the classical orbital radius of the electron bound to the H-like ion is inversely proportional to the atomic number of the projectile and the screening becomes larger for heavier ions.

Finally the present result is compared with the theoretical predictions based on the Born approximation. As for partially stripped ions, a basic treatment was given by Kim and Cheng [16]. Recently, an analytical formula of the fixed-charge stopping powers for H-like light ions of high velocity has been derived by Kaneko [17]. In this treatment, the bound electron of the H-like ion is assumed in the ground state and the projectile excitation was ignored. The excitation of the target atom is described in terms of the inelastic scattering factor. The dipole approximation and the sum rule are utilized in distant collisions and close collisions, respectively. For bare ions, this formula coincides with the Bethe theory of stopping [18]. According to this formula, the fixed-charge stopping power of carbon for 10.4-MeV H^0 is to be 21.8 eV/(μg/cm^2). This value agrees quite well with our result.

IV. CONCLUSIONS

The fixed-charge stopping power of carbon for 10.4-MeV H^0 was measured with the high-resolution magnetic spectrograph. The obtained value is about half of that for H^+ of the same velocity and reproduced quite well by the analytical formula based on the Born approximation. The experimental data are important for a thorough understanding of fast ion-solid interactions. In order to explain the energy loss and the electron-loss cross section of H^0 consistently, a theoretical description taking account of the relation between the impact parameter and the momentum transfer would be required.

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