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Stopping power of carbon for 9.6-MeV/amu H_2^+ ions

Y. Susuki, M. Fritz, K. Kimura, and M. Mannami
Department of Engineering Science, Kyoto University, Kyota 606-01, Japan

N. Sakamoto and H. Ogawa
Department of Physics, Nara Women's University, Nara 630, Japan

I. Katayama
Institute for Nuclear Study, The University of Tokyo, Tanashi 188, Japan

T. Noro and H. Ikegami
Research Center for Nuclear Physics, Osaka University, Ibaragi 567, Japan

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Mean energy losses of foil-transmitted H_2^+ ions are measured for the incidence of 9.6-MeV/amu H_2^+ ions on carbon foils of 1.5–8.5 $\mu g/cm^2$ thickness. The measured ions are those that have traversed the carbon foil without loss of their original electrons. The stopping power of carbon for 9.6-MeV/amu H_2^+ ions, derived from the energy losses, is 55.8 ± 4.6 eV/($\mu g/cm^2$). The obtained stopping power is compared with that calculated with the first Born approximation. The calculated result is slightly larger than the experimental one.

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Dissociation of energetic molecular ions in solids has been extensively studied, and is now successfully applied to the determination of the stereochemical structure of molecular ions [1,2]. Rapid electron loss of the molecular ions near the incident surface of solids results in clusters of interacting bare nuclei for MeV molecular ions composed of light atoms. The cluster undergoes a so-called Coulomb explosion. Since the fragments move faster than the Fermi velocity of valence electrons in solids, the induced polarization charge lags behind the fragments, and under steady-state conditions the polarization wakes move with the fragments [3–6]. The wake induced by a fragment not only acts as a brake on the fragment itself but it modifies the motion of its partner fragment [7]. Energy loss of the exploding fragments has been studied both theoretically [8,9] and experimentally [8,10,11].

Poizat and co-workers have demonstrated that there is a significant probability for MeV H_2^+ ions to be transmitted through thin carbon foils [12–14]. In the subsequent studies of transmission of MeV H_2^+ through thin carbon foils, Cue *et al.* [15,16] have shown that the yield Y of transmitted H_2^+ ions depends on the thickness T of the carbon foil. The yield is expressed as

$$Y(T)=(1-B)e^{-T/\tau v}+Be^{-bT}, \quad (1)$$

where v is the velocity of H_2^+ ions and B, τ, and b are constants. The first term on the right-hand side of Eq. (1) shows the fraction of original H_2^+ ions transmitted through the foil and the second term shows the fraction of H_2^+ ions formed by recombination of fragments after electron capture of proton pairs from the target atoms. Since $B \ll 1$ for MeV H_2^+ ions, τ is interpreted as the lifetime for survival inside the solid of the original molecular ion. The obtained lifetime for H_2^+ ions in carbon is 0.17 fs and does not depend on the projectile energy between 0.4 and 1.2 MeV/amu [15].

For the incidence of a few MeV H_2^+ ions on carbon foils, the original ions are observed only at foils thinner than 1.5 $\mu g/cm^2$ [15], while available self-supporting foils are thicker than 0.5 $\mu g/cm^2$. Therefore most of the previous works are interested in the fragmentation of molecular ions, the energy loss of exploding fragments, or the recombination of fragments. Measurements of the energy loss of the foil-transmitted H_2^+ ions have been also reported only for the reconstituted H_2^+ ions [17–19].

Energy loss of the original H_2^+ ions may depend on the internuclear vector of H_2^+ ions and the wave function of the binding electron. The measurement of the energy loss of the original H_2^+ ions will also give additional information about the dependence of the probability for survival of H_2^+ ions on the orientation of the constituents. Recently, it has been possible to measure the energy loss of the partially stripped hydrogenlike ions at their fixed charge state using a high-resolution spectrometer [20]. The technique can be applied to investigate the energy loss of the original H_2^+ ions.

In this work, we have measured the mean energy losses of 9.6-MeV/amu H_2^+ ions after traversing carbon foils of thicknesses ranging from 1.5 to 8.5 $\mu g/cm^2$. This is a measurement on the energy loss of the original molecular ions traversing solid target at their fixed charge state. We report here our measurement of the energy losses and stopping power of carbon foil for the 9.6-MeV/amu H_2^+ ions.

The experiment was performed using the AVF cyclotron at the Research Center for Nuclear Physics, Osaka University. The ion source used in the experiments was a

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low-voltage arc-type ion source. The momentum-analyzed $H_2{}^+$ ion beam was collimated to have a maximum diameter of 1 mm at the target position, which was the focal point of a high-resolution spectrograph (RAIDEN) [21]. The magnetic field in the momentum-analyzing magnet placed at the beam transport was monitored intermittently during the measurement to calibrate the incident energy of projectiles for each measurement.

Targets were self-supporting carbon foils of thickness ranging from 1.5 to 8.5 $\mu g/cm^2$ and were mounted on a movable ladder holding 12 foils. The thickness of the target foils were measured by the Rutherford backscattering method using 2-MeV He^+ ions from the 4-MV Van de Graaff accelerator of Kyoto University, whose beam diameter was 1 mm at the target position. The measured thicknesses were the mean values of the foil thicknesses. We could not measure thickness inhomogeneity within the diameter of the beam. Only the foils without visible pinholes under an optical microscope were chosen for the targets. In addition, the thickest foil of 8.5 $\mu g/cm^2$ was made with two half-thickness foils to minimize pinholes. Although the pressure around the targets was 10^{-6} Torr during the measurements, we detected no thickening of the foils due to beam irradiation.

Momentum-analyzed ions in RAIDEN were detected with a position-sensitive proportional counter in conjunction with a plastic scintillation counter [20]. Momentum resolution $\Delta p/p$ of the analyzing system was 6×10^{-5} [full width at half-maximum (FWHM)]. The magnetic field in RAIDEN was monitored intermittently during the measurement in order to calibrate the shift of position of detected ions.

We measured the energy spectra of incident ions before and after a measurement of energy spectrum of ions transmitted through a foil. Counting rates of the analyzed ions were kept less than 2×10^2 cps, in order to avoid a possible position shift in the position-sensitive proportional counter. Since a slight change in the beam position at the target gives rise to a shift in the position of energy-analyzed beam in RAIDEN, the ion source of the cyclotron and all the magnets in the beam transport were kept untouched during a set of measurements. The time needed in one set of measurements depended on the thickness of the foil and was about 5–60 min. The transmitted fraction of the $H_2{}^+$ ions was determined from the ratio of the total counts in the energy spectra with and without a foil.

Two examples of the energy spectra of $H_2{}^+$ ions having traversed a carbon foil of 8.0 $\mu g/cm^2$ and of incident ions are shown in Fig. 1. In the energy spectrum of foil-transmitted $H_2{}^+$ ions, only a peak is seen at energies less than a few hundred eV deviated from the peak in the energy spectrum of the incident ions (one channel corresponds to about 77 eV). If the observed ions are reconstituted ones, the change in energy of the $H_2{}^+$ ions is estimated to be greater than 5 keV due to the electron loss of the ions [22]. Thus the observed transmitted ions are not reconstituted ones, and the yield of transmitted $H_2{}^+$ ions decreases exponentially as expressed by the first term of the right-hand side of Eq. (1) as shown in Fig. 2. From a weighted least-squares fit of the transmitted fraction to an exponential function, the dissociation cross section for 9.6-MeV/amu $H_2{}^+$ ions is obtained to be $(1.2\pm0.1)\times10^{-17}$ cm^2. In order to compare the lifetime for survival of the $H_2{}^+$ ions and that for 0.4–1.2-MeV/amu $H_2{}^+$ ions, we have used the atomic density $\rho=1.65$ g/cm^3, which is the density used in the studies for 0.4–1.2-MeV/amu ions [14]. The lifetime τ of the $H_2{}^+$ ions in carbon is 0.23 ± 0.01 fs, which is 1.4 times as large as that of 0.4–1.2-MeV/amu ions [15].

Energy loss of the ions was determined from the shift of the mean energy of the peak in the energy spectrum relative to those of the peaks in energy spectra of incident beam. A full detail of the data processing in order to determine the mean energy loss from the measured energy spectra has been given in Ref. [22]. The obtained result of thickness dependence of the mean energy loss of

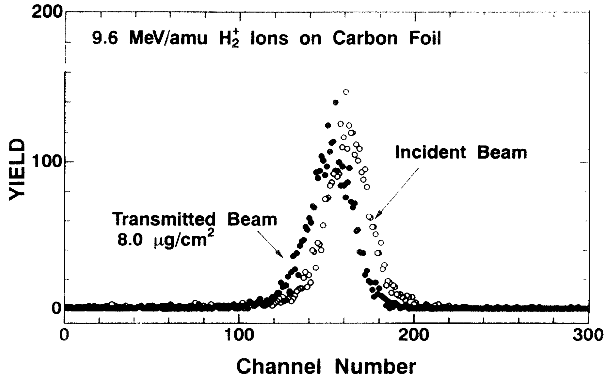

FIG. 1. Examples of the energy spectra of $H_2{}^+$ ions traversed a carbon foil of 8.0 $\mu g/cm^2$ and of the incident ions. One channel corresponds to about 77 eV.

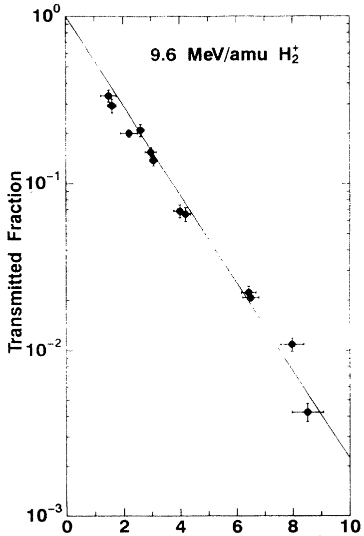

FIG. 2. Dependence of the transmitted fraction of 9.6-MeV/amu $H_2{}^+$ ions on the thickness of the carbon foil. The solid line shows the least-squares fitting to data. The foil of 8.5-$\mu g/cm^2$ thickness was made with two half-thickness foils.

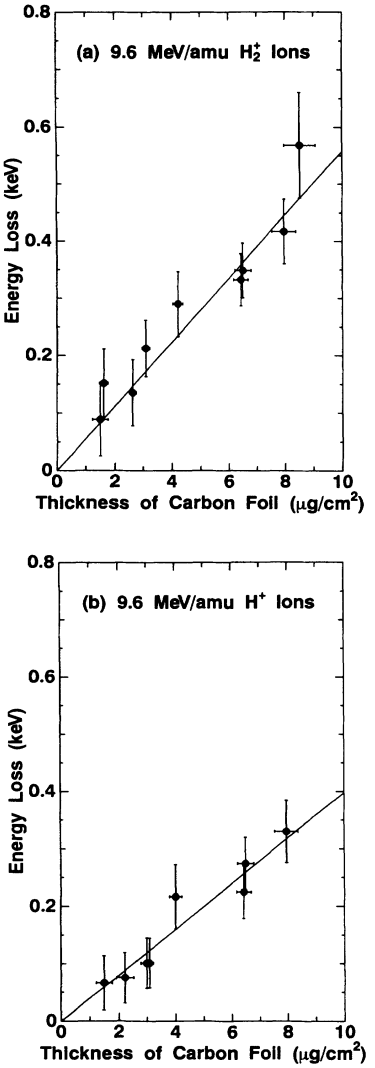

FIG. 3. Thickness dependence of the energy loss of ions transmitted through carbon foil. (a) 9.6-MeV/amu H_2^+ ions and (b) 9.6-MeV/amu H^+ ions. The solid lines show the least-squares fitting to data. The foil of 8.5-μg/cm^2 thickness used at H_2^+ ions incidence was made with two half-thickness foils.

H_2^+ ions is shown in Fig. 3(a). For comparison, thickness dependence of the energy loss of 9.6-MeV H^+ ions is shown in Fig. 3(b). From a weighted least-squares fit of the losses in Fig. 3(b) to a straight line, the stopping power of carbon for 9.6-MeV H^+ ions is determined to be 39.6±4.2 eV/(μg/cm^2). The estimated error contains the standard deviation of data from the straight line, the errors of the energy losses, and those of the foil thicknesses. This agrees well with the compiled stopping power of 42.1 eV/(μg/cm^2) by Andersen and Ziegler [23]. A weighted least-squares fit of the observed energy losses of H_2^+ ions to a straight line is shown in Fig. 3(a). The stopping power derived from the line is 55.8±4.6 eV/(μg/cm^2). This is 1.41 times as large as that for the proton of the same velocity. This ratio is related to the effective charge number Z_{eff} of H_2^+ ions by

$$[Z_{\text{eff}}(H_2^+)]^2 = S(H_2^+)/S(H^+) , \qquad (2)$$

where $S(H_2^+)$ and $S(H^+)$ are the stopping powers for H_2^+ and H^+ ions of the same velocity, respectively. Thus the effective charge number Z_{eff} of H_2^+ ions in carbon is 1.19±0.08.

The experimental stopping power is compared with calculated one using the first Born approximation. A general expression of the electronic stopping power is given by [24]

$$-\frac{dE}{dx} = \frac{8\pi N e^4}{v^2\hbar^2} \sum_n (E_n - E_0) \int_{q_{\min}}^{q_{\max}} \frac{dq}{q^3} |F^{p}_{00}(-\mathbf{q})|^2 \times |F^{t}_{n0}(\mathbf{q})|^2 , \qquad (3)$$

where N is the number density of atoms in carbon, E_n and E_0 are energies of an excited and the ground states of the target atom, $q_{\min} = (E_n - E_0)/\hbar v$, $q_{\max} = 2mv/\hbar$, m is the electron mass, $F^{p}_{00}(-\mathbf{q})$ is the elastic form factor of the projectile, and $F^{t}_{n0}(\mathbf{q}) = \langle n | \sum \exp(i\mathbf{q}\cdot\mathbf{r}_j) | 0 \rangle$ is the transition form factor of the target atom. Now we choose

$$\varphi_{H_2^+}(\mathbf{r}) = \frac{1}{\sqrt{2}} \{\phi_{1s}(\mathbf{r}) + \phi_{1s}(\mathbf{r} - \mathbf{R})\} , \qquad (4)$$

as the zeroth-order approximation to the wave function of H_2^+, where $\phi_{1s}(\mathbf{r})$ is the ground-state wave function of the hydrogen atom and $\mathbf{R}$ is the internuclear vector.

Neglecting the cross term of ϕ_{1s}'s in the calculation of the form factor of the projectile, Eq. (3) for randomly oriented H_2^+ ions reduces to

$$-\frac{dE}{dx} = \frac{8\pi N Z e^4}{m v^2} \int_{I/\hbar v}^{2mv/\hbar} \frac{dq}{q} \left[1 + \frac{\sin(qR)}{qR} \right] \times \left\{ 1 - \frac{1}{2(1 + a_B^2 q^2/4)^2} \right\}^2 , \qquad (5)$$

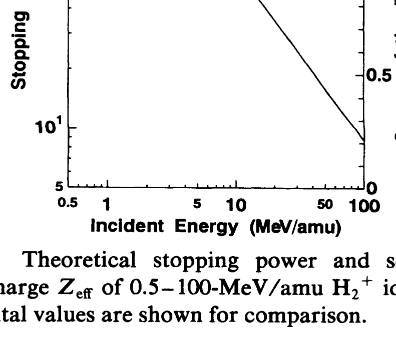

FIG. 4. Theoretical stopping power and square of the effective charge Z_{eff} of 0.5–100-MeV/amu H_2^+ ions in carbon. Experimental values are shown for comparison.

where a_B is the Bohr radius and Z and I are the atomic number and the mean excitation energy of the target atom, respectively.

In the same formalism, the stopping power for proton is expressed as

$$-\frac{dE}{dx}=\frac{4\pi NZe^4}{mv^2}\ln\left[\frac{2mv^2}{I}\right] . \tag{6}$$

Using the most probable value of R to be 1.17 Å [25] and $I=79$ eV [26] in Eqs. (5) and (6), we calculated the stopping power of carbon foil for $H_2{}^+$ and the ratio of that to the stopping power for H^+ ions, i.e., the square of the effective charge number Z_{eff} of the $H_2{}^+$ ion.

Figure 4 shows the calculated stopping power for $H_2{}^+$ ions and the square of the effective charge number Z_{eff} of the $H_2{}^+$ ion, in the energy range from 0.5 to 100 MeV/amu. For 9.6-MeV/amu $H_2{}^+$ ions, the calculated stopping power and Z_{eff}^2 are 65.0 eV/(μg/cm^2) and 1.55, respectively. The calculated values are slightly larger than the experimental ones, 55.8 eV/(μg/cm^2) and 1.41.

The theoretical stopping power has been also obtained by Kaneko for $H_2{}^+$ ions using the degenerate electron gas model and the wave-packet theory [27]. The result agrees with our calculated stopping power. Considering the crude approximation made in deriving the theoretical stopping power, further theoretical study of stopping power for $H_2{}^+$ ions is needed.

In summary, we have measured the stopping power of carbon foil for 9.6-MeV/amu $H_2{}^+$ ions. The stopping power has been calculated for randomly oriented $H_2{}^+$ ions using the Born approximation. The calculated stopping power is slightly larger than the measured one. The experimental data are helpful to the theoretical approach for understanding the excitation of target atoms by $H_2{}^+$ ions and the survival probability of $H_2{}^+$ ions in the foil.

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