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Direct measurement of fixed-charge stopping power for 32-MeV $^3He^{1+}$ in a charge-state nonequilibrium region

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The energy loss of 32-MeV ^3He ions passing through carbon foils of 2–100 $\mu g/cm^2$ thickness was measured with use of a high-resolution magnetic spectrograph. The measurement was made for ions emerging in the same charge state as the incident beam. Energy-loss spectra of $^3He^{1+}$ for thinner foils showed a single peak, while for thicker foils two peaks appeared. From energy-loss spectra with a single peak, the fixed-charge stopping power of carbon for $^3He^{1+}$ at $20.7v_0$ a.u. was deduced. The result was compared with other experiments and theoretical predictions.

The stopping power for fast bare ions of charge Z_1e is proportional to Z_1^2 in the Bethe theory of stopping.[1] In this theory, a projectile is treated as a point charge of Z_1e. When the projectile is not a bare ion, however, a screening effect by its bound electrons must be considered. Thus, the energy loss should depend on the charge state of the projectile in the target material. For channeled ions, the charge-state dependence of the energy loss was measured by Datz *et al.*, from which they discussed the screening effect by bound electrons.[2] In a random target, the contribution to the energy loss is not only from distant collisions but also from close collisions. Therefore, the screening by bound electrons is expected to be less effective. Cowern *et al.*[3] have measured the charge-state dependence of energy losses for 3-MeV/amu light ions in the nonequilibrium region. Their measurement was made for ions emerging from carbon with the same charge state as the incident beam. They analyzed data considering fixed-charge stopping powers and the energy loss in charge-changing collisions.

In the present work, energy losses of 32-MeV ^3He ions passing through thin carbon foils were measured as a function of the foil thickness. Here, measurements were also made for ions emerging in the same charge state as the incident beam. For thinner foils, energy-loss spectra for $^3He^{1+}$ showed a single peak while, for thicker foils, two peaks appeared. From another measurement of the $^3He^{1+}$ beam attenuation in carbon, it was concluded that single-peak spectra correspond to $^3He^{1+}$ ions which passed through the carbon foil without suffering charge-changing collisions. From these spectra, the fixed-charge stopping power of carbon for $^3He^{1+}$ was deduced. The result was compared with stopping powers for channeled ions from a point of view of the screening by bound electrons. Also, a comparison was made with theoretical predictions.

The experiment was performed using the AVF cyclotron at Research Center for Nuclear Physics, Osaka University. The target was self-supported carbon foils. The thickness of them ranged from 2 to 100 $\mu g/cm^2$, which was measured by the Rutherford backscattering (RBS) method using 2-MeV helium beams from the Van de Graaff accelerator at Kyoto University. The energy-loss spectrum of emergent ^{3}He ions was measured with use of a high-resolution magnetic spectrograph RAIDEN.[4] This spectrograph has a large dispersion of 27 000 mm and typically an energy resolution of 1×10^{-4} is realized. Details of the beam-line layout are described elsewhere.[5] The focal-plane counter was a combination of a position-sensitive gas proportional counter and a plastic scintillation counter 1 cm in thickness. The effective length of this counter is about 4 cm.

Figure 1 shows energy-loss spectra for $^3He^{1+}$ and $^3He^{2+}$ measured by RAIDEN. For $^3He^{2+}$, a single peak appears irrespective of the foil thickness and its position shifts to the larger-energy-loss side with increasing foil thickness. On the other hand, the spectra of $^3He^{1+}$ ions are quite different. They show a single peak for thinner foils while two peaks appear for thicker foils and, furthermore, the relative intensity of the smaller-energy-loss component decreases as the foil thickness increases. This behavior in $^3He^{1+}$ spectra seems to be attributed to the onset of charge-changing collisions in the foil.

In order to look into further details, the attenuation of $^3He^{1+}$ beams after passing through a carbon foil was measured as a function of foil thickness t. In the present energy region, the neutral fraction of ^{3}He is negligible and the electron-capture cross section is by several orders of magnitude smaller than the electron-loss cross section. So, the ratio of outgoing $^3He^{1+}$ yields to incident beam intensity is expressed as

$$f(t)=\exp(-\sigma_l t)+\frac{\sigma_c}{\sigma_l}[1-\exp(-\sigma_l t)]\ , \qquad (1)$$

where σ_l and σ_c denote electron-loss and electron-capture cross sections, respectively. Figure 2 shows results. From a least-squares fitting with Eq. (1), σ_l and σ_c were determined to be 5.23×10^{-18} and 8.12×10^{-23} cm^2, respectively. A solid curve in the figure represents the result of the fitting and a dashed line shows the contribu-

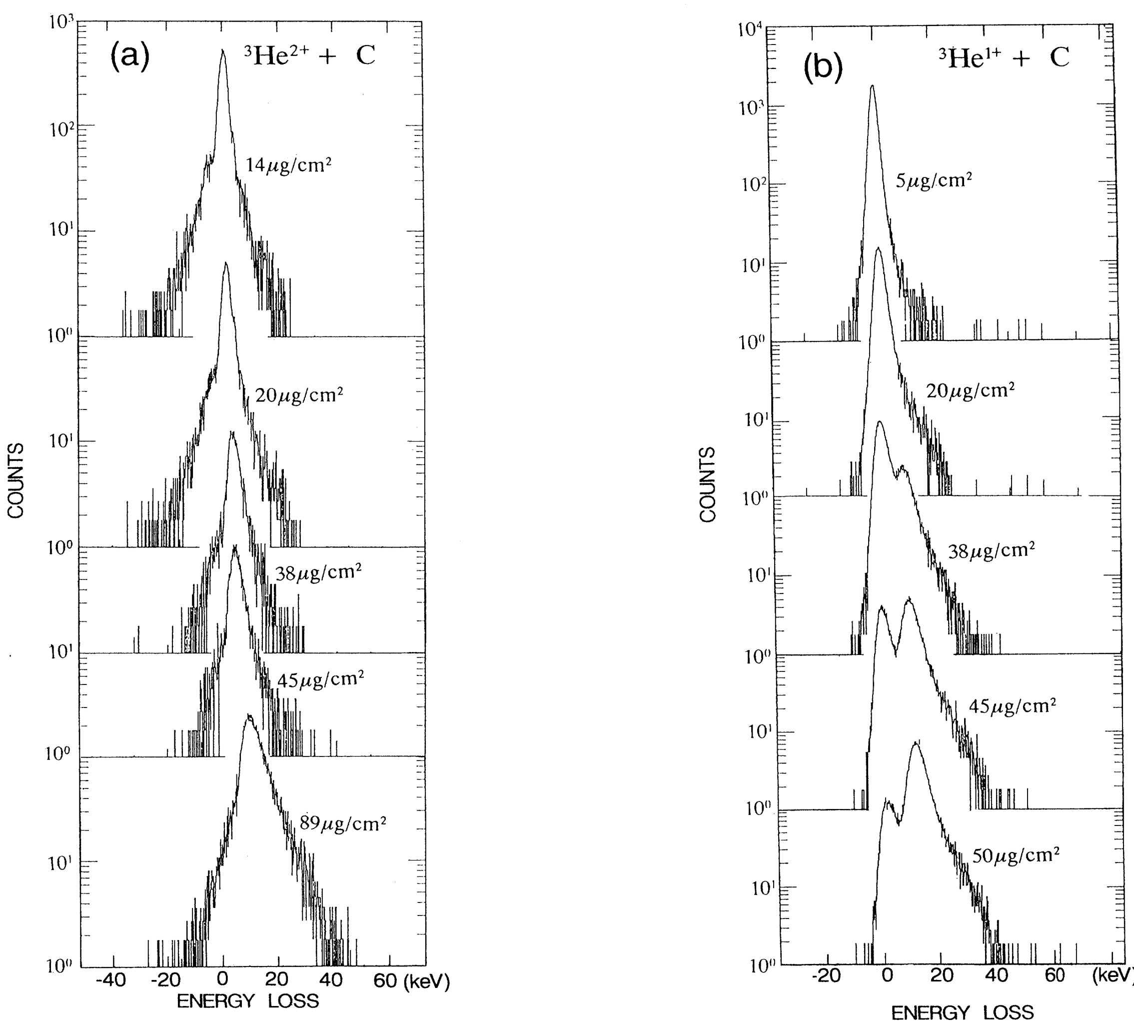

FIG. 1. Typical energy-loss spectra of 32 MeV (a) $^3He^{2+}$ and (b) $^3He^{1+}$ ions after passing through carbon foils. Outgoing ions were in the same charge state as the incident beams.

tion from the first term in Eq. (1). Departure of the data from the dashed line in the thicker foil region is due to the electron capture of stripped $^3He^{2+}$ beams.

For the two-component spectra in Fig. 1(b), a peak shape fitting was carried out and the ratio of the yields for the smaller-energy-loss component to the total yields was deduced. In Fig. 2, open circles denote the $^3He^{1+}$ fraction for the component of the smaller energy loss. They agree very well with the exponentially decaying line. Therefore, the smaller-energy-loss component is understood to correspond to $^3He^{1+}$ ions which passed through the carbon foil without suffering charge-changing collisions.

The energy loss was determined from the difference between the first moment of the energy-loss spectra with and without a target foil. Results for $^3He^{1+}$ and $^3He^{2+}$ are shown in Fig. 3. First, we mention the case for $^3He^{2+}$. Since there is a linear relation between the foil thickness and the energy loss, a least-squares fitting was carried out. The dashed line represents the result. From the tangent of this line, the stopping power was determined to be 156.9±4.9 eV/(μg/cm^2). This value agrees very well with that from the compilation by Ziegler,[6] where ^3He ions are assumed to traverse the foil in the fully stripped state. This agreement is quite reasonable be-

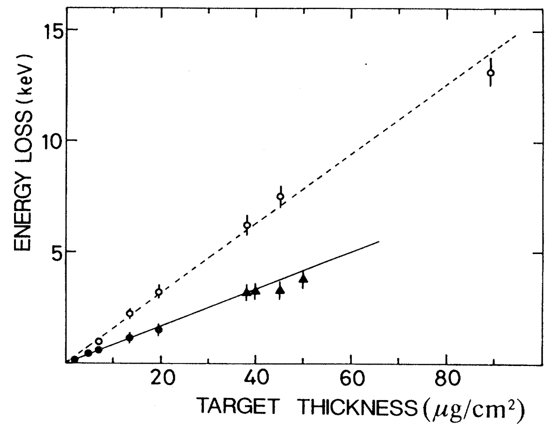

FIG. 3. Foil thickness dependence of the energy loss. Open and solid circles are for $^3He^{2+}$ and $^3He^{1+}$, respectively. Solid triangles are for the smaller-energy-loss component in the two-peak spectrum of $^3He^{1+}$. A dashed line shows the least-squares fitting to data for $^3He^{2+}$. A solid line shows the least-squares fitting to data from single-peak spectra of $^3He^{1+}$.

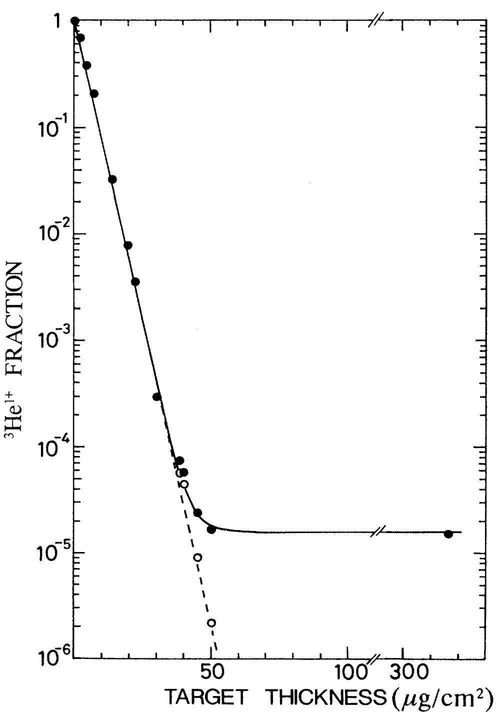

FIG. 2. The attenuation of $^3He^{1+}$ beams after passing through carbon foils. Solid circles are the ratio of outgoing to incident $^3He^{1+}$ ions. Open circles are the contribution from the smaller-energy-loss component in the two-peak spectrum. A solid curve is the result of the least-squares fitting with Eq. (1). A dashed line is the contribution from the first term of Eq. (1).

cause the mean free path of the electron capture is more than 10^3 times larger than the foil thickness used in the present measurement, so the contribution from $^3He^{2+}$ ions, which underwent a series of charge-changing collisions, is negligibly small.

Second, a remark is on the case for $^3He^{1+}$. From the result shown in Fig. 2, it is obvious that the energy loss obtained from single-component spectra for thinner target foils is that of $^3He^{1+}$ ions which traversed the foil with keeping their charge state. The solid line in Fig. 3 shows the result of a least-squares fitting to these data. From this line, the fixed-charge stopping power was determined to be 83.8±8.1 eV/(μg/cm^2). For two-peak spectra, the energy loss of each component was deduced by the peak shape fitting. The results for the smaller-energy-loss component are shown by solid triangles in Fig. 3. They agree quite well with the solid line. Therefore, this is another indication that the smaller-energy-loss component corresponds to $^3He^{1+}$ ions which suffered no charge-changing collisions in the foil.

To understand the behavior of the larger-energy-loss component, we performed another experiment where the momentum change of $^3He^{1+}$ in one cycle of electron-loss and -capture collisions was measured directly. This experiment allowed us to quantitatively explain the energy loss of the larger-energy-loss component. Details will be discussed in our next paper.[7]

The effective charge Z_{eff} for $^3He^{1+}$ was obtained to be 1.46±0.07 from $Z_{eff}=Z_1(S_1/S_2)^{1/2}$, where S_1 and S_2 are fixed-charge stopping powers for $^3He^{1+}$ and $^3He^{2+}$ obtained above. Datz *et al.* have measured stopping powers in Au(111) channels for ions of $Z_1=6-9$ at 2

MeV/amu.[2] From a comparison of stopping powers for bare ions with those for ions having one or two K-shell electrons, they found that the screening per electron, which is defined as $(Z_1 - Z_{\text{eff}})$/(number of bound electrons), was about 0.9 in all cases. In our case, the screening by a bound electron is 0.54 ± 0.07 and significantly smaller than their result. This difference seems to originate in the suppression of close collisions for channeled ions.

In order to compare the observed data with the theoretical prediction, we have calculated the electronic stopping power of carbon for 32-MeV $^3He^{1+}$ and $^3He^{2+}$ ions by means of the solid-type local-electron-density model (LEDM) with the use of the Lindhard dielectric function.[8] Here four electrons per carbon atom are assumed to be in the conduction band and the other two are in the $1s$ core state. As for a projectile, a bound electron in a $^3He^{1+}$ ion is assumed to be in the $1s$ state. Hereby, the spatial distribution of the projectile charge is introduced. The charge distribution of $^3He^{1+}(Z_1=2)$ in $\mathbf{k}$ space is given to be $Z_1 - \langle 1s | e^{ikr} | 1s \rangle$. The other details of the calculation are presented in Ref. 9. As a result, the stopping powers of carbon for $^3He^{1+}$ and $^3He^{2+}$ were obtained as 96.0 and 162.5 eV/(μg/cm^2), respectively. The calculated values are slightly larger than the data. We also compare the data with the analytical result[10] obtained recently on the basis of the Born approximation. According to Ref. 10, the stopping power for hydrogen-like projectiles is expressed as

$$S = (4\pi e^4 N Z_2 / m v^2)[(Z_1 - 1)^2 \ln(2mv^2/I) + (2Z_1 - 1)\ln(v/Z_1 v_0) + Z_1 - \tfrac{11}{12}] , \quad (2)$$

where I, Z_2, and N denote the mean excitation energy, the atomic number, and the number density of the target atom, respectively. If we adopt 77.3 eV for the mean excitation energy of the carbon atom,[11] the calculated stopping power for 32 MeV $^3He^{1+}$ is 93.0 eV/(μg/cm^2). Although this value is a bit larger than the experimental result, they agree well within the error. Finally, we add the comment that the shell correction, the Z^3 correction, and the Bloch correlation totally bring less than 1% change of the stopping power in the present case. So, these corrections were not taken into account.

In conclusion, with a high-resolution magnetic spectrograph, we successfully separated $^3He^{1+}$ ions which suffered a series of charge-changing events from those without suffering charge-changing collisions in the energy-loss spectrum in a charge-state nonequilibrium region. Judging from the comparison between the data and theoretical predictions, we can say that 32-MeV $^3He^{1+}$ ions actually exist inside carbon and bind one electron tightly.

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