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Study on charge equilibration time of highly charged ions in carbon foils*

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Charge state distribution of 0.8MeV/u uranium ions after transmission through a thin carbon foil has been studied. It is observed that the charge state distribution is equilibrated after the uranium ions have passed through a 15 μg/cm^2 carbon foil. The equilibrated average charge state is 33.72 and the charge equilibration time of uranium ions in carbon foil is less than 5.4fs.

Keywords: the radioactive ion beam line in Lanzhou(RIBLL), uranium ions, charge equilibration time
PACC: 2900, 3400, 3470

1. Introduction

The charge state of a fast ion moving through matter fluctuates due to electron loss and capture in collisions with the atoms of the target. After the ions experience a sufficient number of collisions with the target atoms, an equilibrium distribution of charges is established which is dependent on the atomic numbers, velocity of the ions and the target materials.[1,2] During the collision between the ions and the atoms of the target, various processes, such as electron capture, ionization, excitation, vacancy production and the consequent phenomena like energy loss stopping, are closely related to the projectile charge state evolution in the target.[3] The knowledge of charge state distribution of ions after passing through matter is important not only for the study of atomic collision, but also for its application to the design of nuclear instruments. And knowledge of the charge equilibration time of an ion inside a solid is important for an understanding of microscopic deexcitation processes.[4]

The first specific theoretical interest in charge states of heavy ions is aroused in connection with the study of velocity-range relations for fission fragments. In order to estimate the energy loss of the fragments it is necessary to calculate their ionic charge states at all velocities during the slow-down process. Later, in a well-known treatise, Bohr (1948) presented a first extensive theory of charge-changing processes, including some rough estimates for electron capture and loss cross sections for fission fragments.[5] In decades, many experiments about charge state distributions of ions passing through matter have been carried out. Shima *et al*[6] investigated the equilibrium charge state distributions of 35–146 MeV copper ions passing through carbon foils and found that the distributions were related to the effect of the ion shell structure. Imai *et al*[3] studied charge state distributions and the equilibration of distribution with 2 MeV/u sulfur ions passing through various thicknesses of carbon foils. It is observed that the processes involving the L-shell electrons are equilibrated within a target thickness of $\sim$5 μg/cm^2, and for a target thicker than this thickness the charge equilibration is dominated by the K-shell process.[2] Until now there have been performed many experiments studying charge state distributions of ions passing through matter, but the study on charge state distributions of uranium ions passing through matter is carried out very little.

This paper reports on the observation of charge equilibration time of highly charged uranium ions passing through carbon foils.

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2. Experimental setup

The experiment was performed on the Radioactive Ion Beam Line in Lanzhou(RIBLL). And a beam of 0.8 MeV/u $^{238}U^{26+}$ was extracted from the Heavy Ion Research Facility of Lanzhou (HIRFL). Figure 1 shows the layout of the RIBLL and the details can be found in Ref.[7]. In the figure, Q_i and D_i denote the quadrupole and dipole respectively. C_i is the location of the defocusing plane, and T_i indicates the focusing plane ($i = 1, 2, 3, \ldots$).

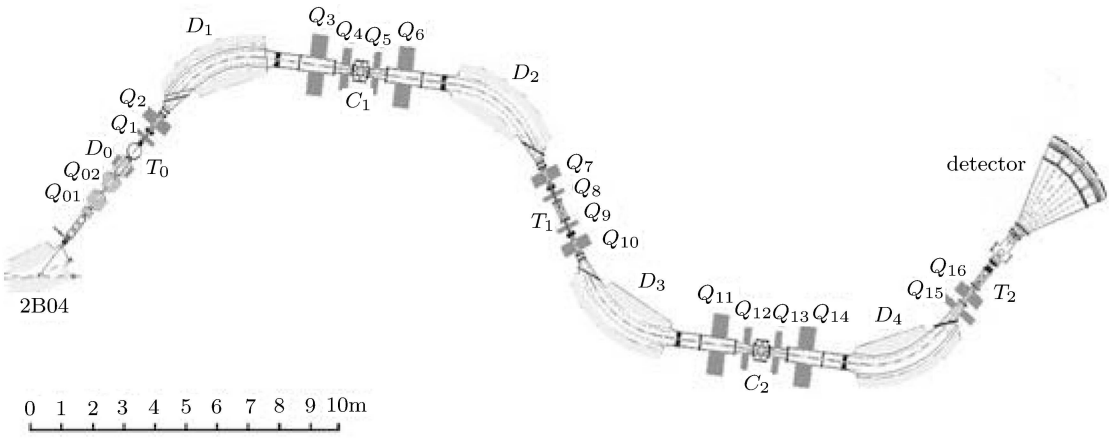


Fig.1. The layout of the RIBLL.

In this experiment, the HIRFL provided an ion beam of 0.8MeV/u $^{238}U^{26+}$. In order to investigate the charge state distributions of $^{238}U^{q+}$ passing through carbon foils, a 0.1 μm carbon foil was installed at T_0, the original primary target location of the RIBLL. After the $^{238}U^{26+}$ ions passed through the carbon foil, $^{238}U^{q+}$ ions were obtained. By appropriately setting the Q_{1-4}, D_1 and the slit at C_1, the ions with a certain charge state could be selected at C_1. After the chosen $^{238}U^{q+}$ ions passed through the carbon foil at C_1, the charge state distribution with the initial charge state of q was measured at T_1 with a silicon detector by scanning the magnetic rigidity of D_2. During the experiment, in order to monitor the beam current for normalization, another Si detector was located at T_0 at an angle of 45° with respect to the beam to count the elastically scattered uranium ions after colliding with the 0.1μm carbon foil.[8] And then, the yield of the normalized uranium ions is

$$Y = \frac{N_{T_1}}{N_{T_0}}, \tag{1}$$

where N_{T_1} and N_{T_0} are the counting rates of the Si detectors at T_1 and T_0, respectively.

In this experiment, the initial charge states of the uranium ions with 29+, 34+ and 39+ were selected at C_1, and charge state distributions of these ions passing through the carbon foils with thicknesses of 5 μg/cm^2 and 15μg/cm^2 at C_1 were measured.

3. Experimental results and discussion

Figure 2 shows a typical distribution of the charge states measured at T_1. By fitting each peak with the Gaussian distribution, the area of each peak can be extracted. Then the distribution of the charge states versus the fraction of each charge state can be obtained. Figure 3 shows such a distribution for $^{238}U^{29+}$ ions passing through a 5μg/cm^2 carbon foil. The error bar represents both statistic error and Gaussian fitting error. By fitting the distribution shown in Fig.3, the average charge state $q_{\rm ave}$ of the uranium ions passing through the carbon foils is obtained. In a similar way, the values of $q_{\rm ave}$ for different initial charge states of uranium ions (q=29+, 34+ and 39+) passing through different thickness carbon foils (5μg/cm^2, 15μg/cm^2) can be obtained.

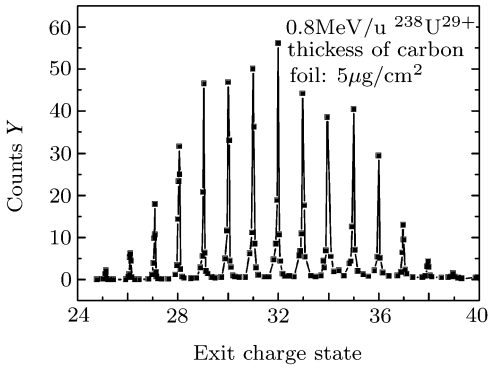


Fig.2. The dependence of the counting rate of exit uranium ions on the exit charge state of uranium ions.

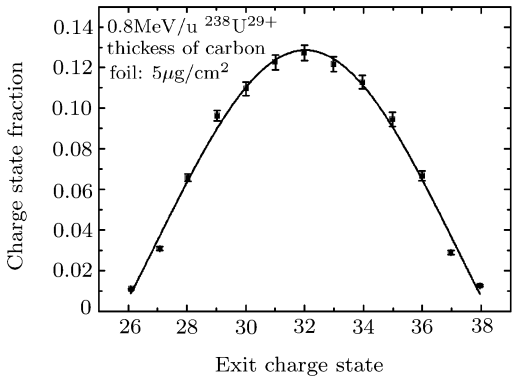


Fig.3. Charge state distribution of 0.8 MeV/u $^{238}U^{29+}$ ionsafter transmission through a 5 μg/cm^2 carbon foil.

Figure 4 shows the dependence of $q_{\rm ave}$ of the exit uranium ions on initial charge state. Open square denotes the $q_{\rm ave}$ of $U^{29,34,39+}$ passing through a 5μg/cm^2 carbon foil. Solid circle represents the $q_{\rm ave}$ of the same ions passing through a 15μg/cm^2 carbon foil. From Fig.4 one can find that the $q_{\rm ave}$ of $U^{29,34,39+}$ ions passing through a 5μg/cm^2 carbon foil changes with initial charge state. But when $U^{29,34,39+}$ ions pass through a 15μg/cm^2 carbon foil, the average charge states keep almost uncharged within the error bar, and they are 33.77+(±0.14), 33.68+(±0.11), and 33.71+(±0.13). It can be concluded that when the 0.8 MeV/u uranium ions pass through a 5μg/cm^2 carbon foil, the charge state distribution is not equilibrated; when passing through a 15μg/cm^2 carbon foil, the equilibration of the charge state distribution is established. Through averaging the charge states, we obtain the equilibrated average charge state to be 33.72+. The speed of 0.8MeV/u uranium ions is 5.6ν_0 (ν_0=2.19×10^{6}m/s, the Bohr speed), so the charge equilibration time for uranium ions in carbon foil is less than 5.4fs (corresponding to the time taken by the uranium ions to pass through a 15μg/cm^2 carbon foil).

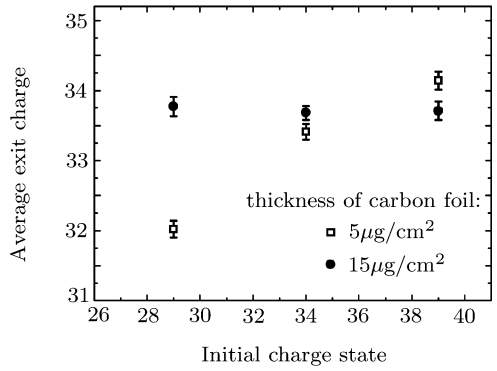


Fig.4. $q_{\rm ave}$ for $^{238}U^{q+}$ after transmission through carbon foils vs initial charge state.

Schiwietz and Grande[9] accumulated about 850 sets of different experimental data and deduced an empirical relation to calculate the equilibrated average charge state of ions passing through solid matter. The relation is

$$Q_{\rm mean}/Z_{\rm p} = \frac{12x + x^4}{0.07/x + 6 + 0.3x^{0.5} + 10.37x + x^4}, \quad (2)$$

$$x = (v_{\rm p}/v_0 Z_{\rm P}^{-0.52} Z_{\rm t}^{-0.019 z_{\rm P}^{-0.52} v_{\rm p}/v_0}/1.68)^{1+1.8/Z_{\rm p}}.$$

The relation is valid for $Z_{\rm p} > 3$ and $\nu_{\rm p} > 0.8\nu_0$. Here, $Z_{\rm p}$ and $Z_{\rm t}$ are the atomic numbers of the projectile and the target respectively, ν_0 is the Bohr speed and $\nu_{\rm p}$ is the speed of the projectile. From Eq.(2) it can be seen that the equilibrated average charge state of ions is dependent on the atomic number of the projectile, the atomic number of the target, the speed of the projectile and the initial charge state of the projectile. This is consistent with our experimental results. Based on Eq.(2), the equilibrated average charge state of 0.8 MeV/u uranium ions passing through carbon foils is 35.35, which is larger than our experimental data 33.72. This discrepancy may come from lack of the experimental data for heavy ions such as uranium ions when Eq.(2) was established.

Hattass *et al*[4] investigated the charge equilibration time of slow $\nu < 0.5\nu_0$, highly charged ion in solids. It is observed that charge equilibration time is determined directly from the dependences of exit charge state on projectile speed ($0.5\times10^6 < \nu < 10^6$ m/s) and foil thickness (5–10nm). Ions like Xe^{44+} and Au^{68+} are found to equilibrate inside a solid in a time of only 7fs. In our experiment, the speed of the uranium ions is 5.6ν_0 (energy is 0.8 MeV/u), the extracted charge equilibration time is less than 5.4fs.

4. Conclusions

In summary, we investigate the charge state distribution of 0.8MeV/u uranium ions passing through a carbon foil at RIBLL. It is observed that the charge state distribution does not equilibrate when 0.8MeV/u uranium ions passing through a $5\mu g/cm^2$ carbon foil. But when the uranium ions passing through a $15\mu g/cm^2$ carbon foil, the charge state distribution is equilibrated and the equilibrated average charge state is 33.72+. This result is consistent with the calculation from the formula given by Schiwietz and Grande. And we obtain the charge equilibration time of uranium ions in carbon foil to be less than 5.4fs.

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