Charge equilibration of laser-accelerated carbon ions in a porous-structure foam target

Bubo Ma,[1] Jieru Ren,[1,*] Lirong Liu,[1] Wenqing Wei,[1] Benzheng Chen,[1] Shizheng Zhang,[1] Hao Xu,[1] Zhongmin Hu,[1] Fangfang Li,[1] Xing Wang,[1] Wenxuan Li,[1] Qiuyan Li,[1] Shuai Yin,[1] Jianhua Feng,[1] Xianming Zhou,[1] Yifang Gao,[1] Yuan Li,[1] Xiaohua Shi,[1] Jianxing Li,[1] Xueguang Ren,[1] Zhongfeng Xu,[1] Zhigang Deng,[2] Wei Qi,[2] Shaoyi Wang,[2] Quanping Fan,[2] Bo Cui,[2] Weiwu Wang,[2] Zongqiang Yuan,[2] Jian Teng,[2] Yuchi Wu,[2] Zhurong Cao,[2] Zongqing Zhao,[2] Yuqiu Gu,[2] Leifeng Cao,[3] Shaoping Zhu,[2,4,5] Rui Cheng,[6] Yu Lei,[6] Zhao Wang,[6] Zexian Zhou,[6] Guoqing Xiao,[6] Hongwei Zhao,[6] Dieter H. H. Hoffmann,[1] Weimin Zhou,[2] and Yongtao Zhao[1,†]

[1]*MOE Key Laboratory for Nonequilibrium Synthesis and Modulation of Condensed Matter, School of Science, Xi'an Jiaotong University, Xi'an 710049, China*
[2]*Science and Technology on Plasma Physics Laboratory, Laser Fusion Research Center, China Academy of Engineering Physics, Mianyang 621900, China*
[3]*Advanced Materials Testing Technology Research Center, Shenzhen University of Technology, Shenzhen 518118, China*
[4]*Institute of Applied Physics and Computational Mathematics, Beijing 100094, China*
[5]*Graduate School, China Academy of Engineering Physics, Beijing 100088, China*
[6]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 710049, China*

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The equilibrium charge state distribution of laser-accelerated carbon ions traversing a tri-cellulose-acetate (TCA, $C_9H_{16}O_8$) foam target was measured experimentally. The ions were generated through the target normal sheath acceleration mechanism. This allowed us to obtain the equilibrium charge state for a wide energy range near the maximum energy loss within a single laser shot. The foam had a porous structure with 2 mg/cm^3 volume density, which is between the typical density of gas- and solid-state matter. We found that the measured average equilibrium charge states were significantly underestimated by theoretical models applicable for gas targets, while were in close agreement with both semiempirical formulas and rate equation predictions based on ion-solid interactions. The solid-density fiber filaments in the current foam structure were attributed and demonstrated. The target density effects, which increase the ionization probability through frequent collisions and decrease the electron capture probability, were proven to play an important role in the foam target. Since the foam targets are widely used in laser plasma interaction experiments, our findings are relevant for a broad range of applications.

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I. INTRODUCTION

Since the invention of aerogel by Kistler in 1931 from sodium silicate [1], a tremendous development of material with density between a gaseous state and a solid state has taken place [2]. Today aerogel, jelly, or foam targets are readily available. These are highly porous materials where more than 99% of the volume void, and they serve many applications, e.g., storage of gases, as filter material, Cherenkov detectors, or insulation, just to name a few. In laser plasma interaction experiments, foam targets are now popular for enhanced charged particle generation and acceleration due to the high-energy coupling efficiency with laser pulses [3–5]. Foam targets have also been applied in recent experiments investigating the ion-plasma interactions [6,7]. The porous structure of the foam can induce high complexity of the charged particle transport process due to collective effects [8]. Therefore, it is important to investigate the details of beam target interaction with this material.

Charge exchange processes in interaction of ions with matter are an important topic of atomic physics. They involve complex dynamic processes of collisional ionization and capture of electrons and influence the ion charge state distribution [9–11] and energy loss of ions [12–18]. Therefore, charge exchange processes are important in the applications of swift heavy ions in material science, applications in medicine and biology, and last but not least the physics of fusion. These processes also play an important role at heavy ion accelerator facilities, where gaseous or solid targets are used to generate highly charged ions to improve the acceleration efficiency of ion beams [19–23]. A very well-known example is the stripper target at GSI-Helmholtzzentrum, where a stripper target was placed between the Alvarez- and Wideröe section at 1.4 MeV/u [24].

In matter, the ion charge state stabilizes at an equilibrium value after a short distance and from then starts to decrease with decreasing velocity of the ion, following approximately the Bohr criterion. For solid-state and gaseous targets [25–30], a vast number of experimental data exist that constitute a solid basis for theoretical models. The charge state evolution is well understood in principle and depends on the dynamic equilibrium of electron capture and ionization rates. It was

*renjieru@xjtu.edu.cn
†zhaoyongtao@xjtu.edu.cn

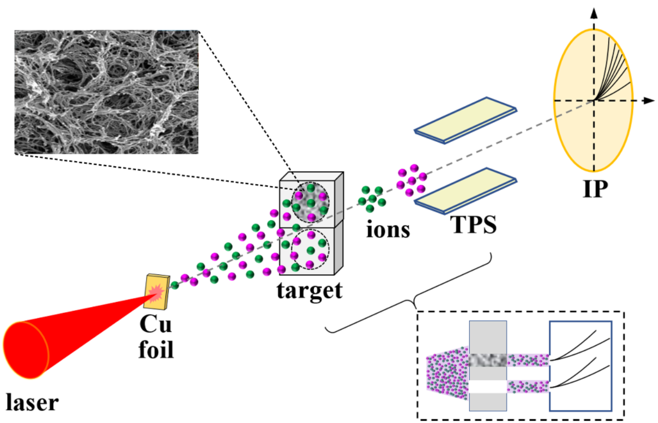

FIG. 1. Experimental setup. A picosecond laser is focused onto a copper foil, generating an intense short pulse of ions through the TNSA mechanism. The energy spectra of carbon ions passing through the foam target and the empty hole were measured with a dual-channel TPS coupled to the Fuji BAS-TR-type image plate (IP).

demonstrated that, in comparison with a gaseous target, the ions passing through a solid target at a similar line density show a markedly higher average charge state [24]. This is known as the density effects caused by the high collision frequency that quenches the lifetime of excited states in solid targets as compared to gas targets [31,32]. However, for the matter with density between gas and solid, very few data exist to pin down the charge state evolution behavior, especially in the energy range near the maximum energy loss.

Here in this work, we performed measurements of the carbon ion charge state equilibration employing a tri-cellulose-acetate (TCA, $C_9H_{16}O_8$) foam with a 2 mg/cm^3 volume density that is between the typical density of gas and solid-state matter. By using laser-accelerated carbon ions, the equilibrated charge states were obtained for a wide-energy range of 5–12 MeV in a single laser shot. The measured average equilibrium charge state in different shots was well-reproduced and compared with various semiempirical theoretical models and rate equations for gas and solid targets. Close agreement with theoretical-prediction-based ion-solid interactions was obtained. This can be explained by the fact that the near-solid-state fiber filament in the foam play the dominant role determining the charge state. The density effect in the foam target was demonstrated.

II. EXPERIMENTAL SETUP

The experiment was carried out at the XG III laser facility of the Laser Fusion Research Center in Mianyang, China. The schematic setup of the experiment is shown in Fig. 1. A 10-μm copper foil was irradiated by a *p*-polarized laser pulse of 1053 nm in central wavelength, 130 J energy, a 10-μm focal spot, and a 843-ps duration at an incident angle of 10° to generate a short-pulse intense ion beam through the target normal sheath acceleration (TNSA) mechanism. The ion beam [33–35] consisted of protons and carbon ions with different charge states and a wide spectrum of kinetic energy. Here only carbon ions are discussed.

The target is a TCA foam fabricated through the *in situ* synthesis method. The foam had a porous structure with a void pore radius mostly less than 2 μm and fiber filaments with radii mostly between 10 and 50 nm, as shown in the upper left corner of Fig. 1. The thickness in the direction of ion propagation was 1 mm. The volume density was about 2 mg/cm^3. The line density was benchmarked by measuring the energy loss of α particles from radioactive sources [7]. We previously used this foam in a series of experiments for laser acceleration, ion stopping [7,36–38], laboratory astrophysics [39], and charge exchange process in plasma [6].

The laser-accelerated ions were directed onto the foam target and simultaneously at an empty channel (no foam case). In combination with the dual-channel Thompson parabola spectrometer (TPS), the energy spectra of carbon ions before and after interaction with the foam target were be obtained simultaneously in one laser shot.

III. RESULTS AND DISCUSSION

The measured spectra of laser-accelerated proton and carbon ions with and without the foam target are shown in Fig. 2(a) together with simulated deflection curves indicated by red dashed lines. The X and Y axis represent the deflection distance by the magnetic field (B) and the electrical field (E) of the TPS. The zero points originate from the neutral particles like photons as well as hydrogen and carbon atoms. The protons and carbon ions of different charge states are very well resolved, and the dominant carbon ion species are C^{6+}, C^{5+}, C^{4+}, and C^{3+}.

The measured deflection distance of the carbon ions for the cases without and with foam in Fig. 2(a) were converted to energies in the range of 5 to 11.5 MeV in Figs. 2(b) and 2(c). The energy spectra of the carbon ions after passing through the foam are obviously changed due to both the charge transfer process and the stopping process. Most notably, the number of C^{4+} ions was significantly reduced about 3.5 times compared to the maximum value. Another apparent change occurs with respect to the highly ionized charged states of C^{5+} and C^{6+}, where the particle numbers increase significantly in the high-energy range.

Figure 3(a) shows the equilibrated average charge states $\overline{Q}(E) = \sum_q qF_q(E)$ of the exiting carbon ions, where $F_q(E)$ is the fraction of carbon ions in charge state q and kinetic energy E, and $\overline{Q}(E)$ is a function of the kinetic energy for two shots. The measured average charge states of carbon ions passing through the foam were very well reproducible, which implies that the charge states were in equilibrium distribution. For comparison, the laser-accelerated carbon ions without target interaction are presented in Fig. 3(b). The average charge state of the initial laser-accelerated carbon ions is less than 4.4 in the investigated energy range. As shown in Fig. 3(d), the dominant species is C^{4+}. However, after interacting with the foam target, the average charge state increased. For example, for carbon ions at kinetic energy of 11 MeV, the average charge state is enhanced by about 17% from 4.2 to 4.9. Besides, after interacting with the foam target, the average charge state increased monotonously with the kinetic energy. That means that, with increasing energy, the fractions of highly ionized carbon ions (C^{5+} and C^{6+}) are evidently increased. This is consistently shown in Fig. 3(c).

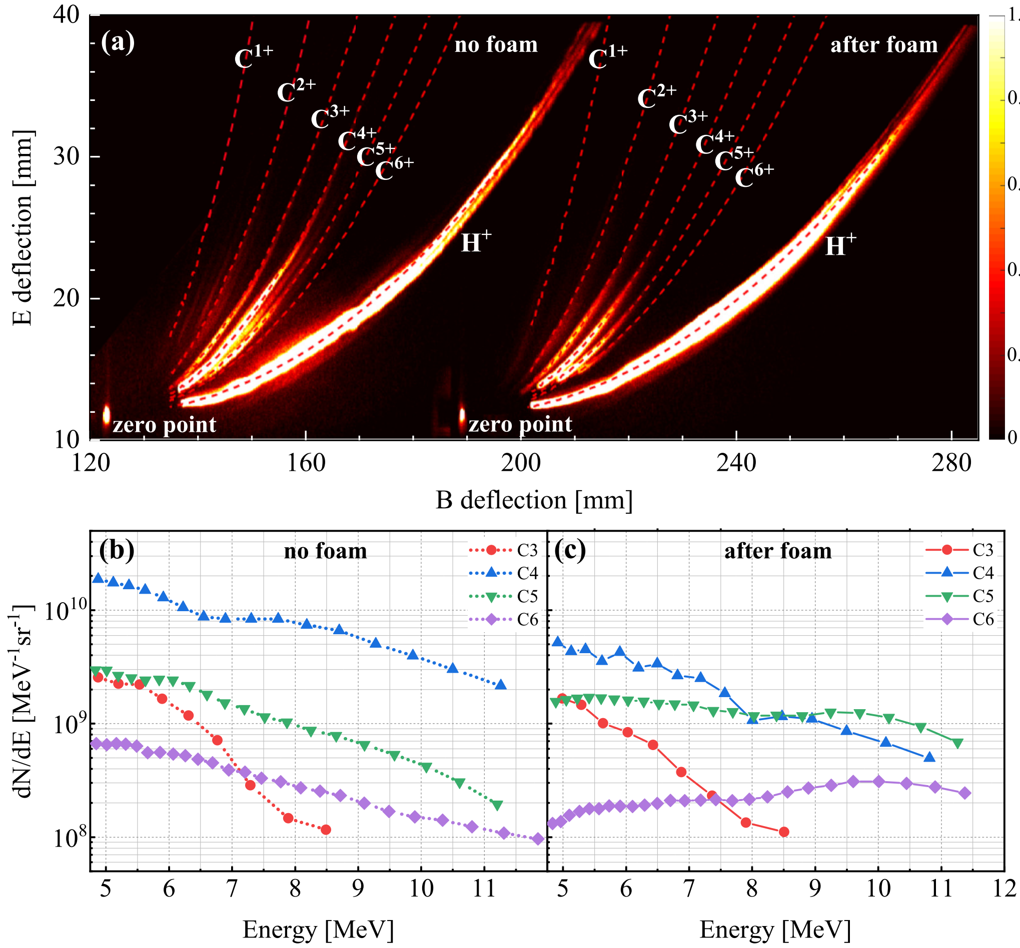

FIG. 2. (a) Typical deflection curves of laser-accelerated carbon ions without target (left) and passing through the foam (right). The converted energy spectra of carbon ions (b) without target and (c) passing through the foam.

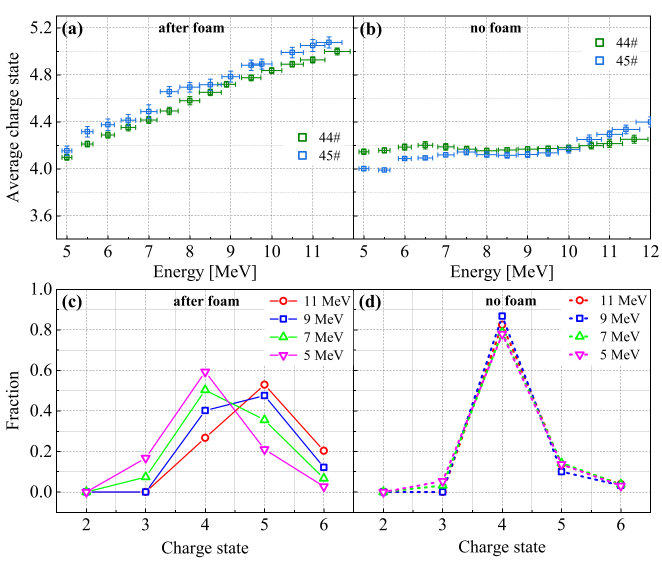

FIG. 3. Average charge states of carbon ions passing through foam (a) and without any target (b) for two shots. The error concerning energy and charge state originates the energy resolution of the TPS and statistical error, respectively. Charge state distribution evolution of carbon ions passing through foam (c) and without any target (d) versus kinetic energy.

In Fig. 4(a), the measured average equilibrium charge states are compared to the commonly used semiempirical formulas [40–46] that have been developed for ion interactions with solids based on the analytical expression of effective charge developed from Bohr's stripping criterion [47] and Schiwietz and Grande's fitting formula [44]. Most of the models can well predict the results, except for Basko's formula [43], which added the dependence of the Coulomb logarithm on Z and was more applicable for the particles with atomic number $Z \geqslant 20$. Besides, the Nikolaev-Dmitriev model [45] underestimates our results at higher energies of 9–12 MeV.

In Fig. 4(b), the measured average equilibrium charge states are compared to the rate equation predictions using tabulated cross sections for the charge changing cross sections (CCCS) code [48,49] for gas and solid targets considering single-electron (SE) and double-electron (DE) transfer processes, respectively. When the cross sections of the gas target were employed, the charge states were greatly underestimated. Once the cross sections of the solid target were employed, the theoretical equilibrated charge states were obviously enhanced and approached our experimental data.

The enhancement employing solid-target cross-section data compared with gas-target predictions was attributed to the target density effect in dense matter, which will on one hand increase the electron loss rate because of

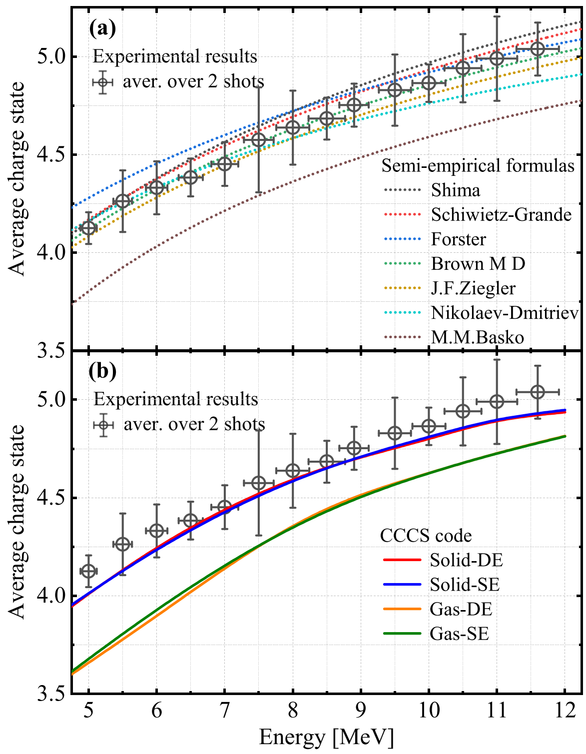

FIG. 4. The comparison of measured average charge states with theoretical predictions. The experimental data were averaged over two shots with errors representing the shot-to-shot fluctuations and statistical error. (a) The comparison with semiempirical models. (b) The comparison with predictions through solving rate equations.

the two-step process—electron excitation and subsequent ionization in the secondary collision, and on the other hand decrease the electron capture rates because of the easy ionization of highly excited electrons that are captured from previous collisions.

The close agreement of experimental data with rate equation predictions with solid-target cross sections can be explained as follows. The foam consists of fiber filaments and void pores. The charge states of carbon ions passing through layers of fiber filaments with pore-scale intervals are indeed measured. The agreement indicated that the filament of the foam is in a solid state. This is different from the homogeneous plasma case with the same volume density discussed in Ref. [6], where the measured charge states of the carbon ions are between the typical gas- and solid-density predictions.

It was also shown in Fig. 4(b) that the double-electron transfer processes had negligible influence on the average charge state. The charge transfer rates for the single-electron and double-electron transfer processes of 6-MeV carbon atom and ions with foam in a solid state are listed in Table I, where the double-electron process contributes synchronously to the increase in electron loss and capture rates; therefore, the effects on the charge states are mutually subtracted.

IV. SUMMARY

In summary, the equilibrated charge state distributions of laser-accelerated short-pulse carbon ions penetrating through the foam targets with energy near the maximum energy loss were measured. The average charge state of ions after the foam are well reproducible. The stripping effect of foam on incident ions was clearly presented compared to the data without targets. The average charge states agree well with most of the semiempirical formulas based on ion-solid interactions except for Basko's formula, which was more applicable for the particles with an atomic number larger than 20. To deeply understand the charge transfer processes, the rate equations were solved with cross-section data from the CCCS code for both gas and solid targets. When cross sections for solid targets were employed, the charge states were obviously enhanced and are in closer agreement with our experimental results. That demonstrated the important role of target density effects in foam targets which can increase the ionization rates and decrease the electron capture rates. It was also shown that the double-electron loss and capture processes have negligible influence on the charge states. Considering that the foam targets are widely used in laser plasma interaction experiments to enhance the laser-accelerated particle brilliance and ion-plasma interaction experiments to obtain high-precision data in transient plasma, our results provide important data for communities studying high-energy density physics and accelerator technologies, as well as for applications in medical, biological, and material fields. This method provides an alternative approach to measure the charge state distribution of swift heavy ions in matter over a broad energy range in a single laser shot.

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TABLE I. The charge transfer rates ($\times 10^{12}$ s^{-1}) for 6-MeV carbon ions with foam target.

Charge state	Single-electron loss	Double-electron loss	Single-electron capture	Double-electron capture
C^{0+}	76.93	13.08		
C^{1+}	73.04	12.42	0.27	
C^{2+}	51.08	8.68	0.63	0.11
C^{3+}	12.27	2.09	1.51	0.26
C^{4+}	4.89	0.83	3.42	0.58
C^{5+}	0.46		6.74	1.15
C^{6+}			13.50	2.29

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