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Review article

Review of stopping power and Coulomb explosion for molecular ion in plasmas

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Abstract

We summarize our theoretical studies for stopping power of energetic heavy ion, diatomic molecular ions and small clusters penetrating through plasmas. As a relevant research field for the heavy ion inertial confinement fusion (HICF), we lay the emphasis on the dynamic polarization and correlation effects of the constituent ion within the molecular ion and cluster for stopping power in order to disclose the role of the vicinage effect on the Coulomb explosion and energy deposition of molecules and clusters in plasma. On the other hand, as a promising scheme for ICF, both a strong laser field and an intense ion beam are used to irradiate a plasma target. So the influence of a strong laser field on stopping power is significant. We discussed a large range of laser and plasma parameters on the coulomb explosion and stopping power for correlated-ion cluster and C_{60} cluster. Furthermore, in order to indicate the effects of different cluster types and sizes on the stopping power, a comparison is made for hydrogen and carbon clusters. In addition, the deflection of molecular axis for diatomic molecules during the Coulomb explosion is also given for the cases both in the presence of a laser field and laser free. Finally, a future experimental scheme is put forward to measure molecular ion stopping power in plasmas in Xi’an Jiaotong University of China.

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1. Introduction

Energy loss of ions propagating in plasmas has been a subject of research for several decades because it has lots of applications in many different fields of science such as inertial confinement fusion, plasma diagnostics, and medical applications [1–5]. In particular, interactions of energetic molecular ion or cluster ion beams with matter have attracted a lot of attention due to their good quality in many aspects [6–9]. One of the most obvious advantages that relates to the cluster ion is the effect due to a very low charge to mass ratio. As a result, a cluster ion beam at any given current density can transport up to thousands of times more atoms than a monomer ion beam does at the same current density. This will allow the cluster ion beam to be focused to an extremely small focal spot compared to that in the case of conventional heavy ions. Another advantage of cluster ion beam is that they can transport a large number of low-energy atoms even when the total energy of the accelerated cluster ions is high. However, it is very difficult to realize such a process with conventional monomer ion [8,9]. Driven by the recent developments in the experimental

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accelerator techniques for cluster ion beams [10] and laser technology [11], a promising inertial confinement fusion scheme is proposed [12,13], in which a plasma target is irradiated simultaneously by both an intense ion beam and a laser beam. Such experiments usually can be carried out with the following setup: A thin foil of solid material is irradiated with a laser pulse so it becomes a hot dense plasma. At the same time, an ion beam is sent into the material in the opposite direction. Several experiments [14−17] have been carried out to measure the stopping power and charge variation of heavy ion beams in the laser-ablated plasma targets and warm dense plasma [18]. The experimental results show that the energy loss of projectiles in plasmas is larger than that in cold matter (solid and gases) because of the special properties of the plasma. In the case of plasmas, interactions can happen not only between projectile particles with neutral atoms and bound electrons, but also with ions and free electrons. There are two main reasons to explain enhanced plasma energy loss: one is the increase of projectile charge state due to the reduction of the capture cross sections with target free electrons, and the other is the more efficient energy transfer with free electrons of plasmas.

In theoretical aspects, molecular dynamic simulations are mainly used to study the classical stopping power [19]. The main existing theoretical models include linear and nonlinear Vlasov−Poisson theory [20−25], and the binary collision theory [26]. Besides stopping power, charge state is a prerequisite and another focus of attention [27−29]. For the molecular ions and clusters, several authors have reviewed the development of molecules and clusters propagating in different targets especially in solids [30−33]. However, the interaction of charged molecular ion beam with plasma is still not totally understood. In particular, the experimental data about molecular ions traveling in plasmas are very rare so far. Thus, it is very urgent to carry out the research especially for experiments in this field.

The interaction of an energetic molecule with a plasma target is very different from an individual ion. It can be described by the basic processes as following: In the first stage, the molecule loses the valence electrons in the collisions with plasmas and the molecular structural stability will be broken due to the ionization of its constituent atoms. Subsequently, the ions will lose their energy because they transfer their kinetic energies to the target, at the same time, the repulsion aroused by the dynamically screened Coulomb interaction between the like-charged ions drives them apart and the molecular ion will experience the course of Coulomb explosion. After original break-up of the molecule, its further moving is accompanied by electronic excitations of the target, which show strong interference because of close spatial correlation within the ions, which is known as the vicinage effect. Such an interference aroused by the structure is expected to produce an enhanced stopping power for each ion when compared to the energy loss of a monomer ion traveling at the same speed, as long as the inter-ionic distances within the cluster are smaller than the characteristic length for the electronic excitation. Due to the difference between individual ions, vicinage effect attracts more concerns for molecular ions or cluster slowing down in plasma. Several authors [34−40] have adopted linear Vlasov−Poisson theory to study the energy loss of molecular ions or clusters in plasma targets. However, the Coulomb explosion hasn't been considered in their works. It is well known that, the Coulomb explosion is a very interesting phenomenon for the molecules and clusters propagating in plasmas. It can not only change the shape and structure of clusters, but also influence the stopping power to reach a more transparent information.

On the other hand, driven by the development of experiments, the influence of a high-intensity laser field on the energy loss has been studied by theoretical researchers. As a pioneer, Arista firstly adopted a general formulation based upon a time-dependent Hamiltonian. He described the influences of a strong laser field on the energy loss of an energetic ion traveling in a degenerate electron gas [41]. In the plasma case, the study results were as follows: When the projectile speed was less than the plasma electron thermal speed, the laser field decreased the energy losses [12]. While in the high-intensity limit, projectile particles might be accelerated by the laser field [20]. The influence of the laser field on the energy loss of ion clusters penetrating in hot plasma has been studied by Silva and Galvão [42]. When compared to a laser-free case, the study results showed that the laser field affected the vicinage effect aroused by the spatial correlation among the cluster constituent particles and caused a decrease of the energy loss. Furthermore, the energy loss of ions in plasmas irradiated by an intense laser field was studied by Nersisyan and Deutsch. It was found that the laser field might strongly reduce the mean energy loss for slow ions when increasing it at high speeds [43]. Moreover, Hu et al. adopted a two-dimensional particle-in-cell simulation to study the dynamic polarization and energy loss for an energetic ion beam moving through a two-component plasma, which was simultaneously irradiated by a strong laser pulse [44]. In our works, the energy loss, Coulomb explosion and laser effects for molecular ion and clusters in plasma are considered based on the molecular dynamic (MD) simulation [45−50]. In order to get more clear information about molecular ions and cluster interaction with plasma targets, especially about Coulomb explosion and laser effects, we summarize our recent theoretical studies about molecular ions and clusters propagating through plasma targets. In this review paper, we focus on discussing the influences of laser effects, plasma parameters, vicinage effects and cluster size on Coulomb explosion and stopping power. In particular, a comparison is made for hydrogen clusters and carbon clusters on the stopping power. In addition, considering the scarcity of experimental data about molecular ion propagating in plasma, a future experimental scheme is put forward to measure the stopping power. It will be carried out by our cooperators in Xi'an Jiaotong University in the future.

The paper is organized as follows. In Sec. 2, following the theoretical model, the heavy ion stopping power in plasma is discussed. Then, the interaction potential, stopping power and Coulomb explosion for diatomic molecular hydrogen and C_{20} cluster traveling in plasmas are given. In Sec. 3, a large range of plasma parameters on Coulomb explosion and stopping power

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