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Research Article

Energy loss of an energetic Ga ion in hot Au plasmas

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Abstract

Self-consistent calculations of energy loss for a Ga ion moving in hot Au plasmas are made under the assumption of wide ranges of the projectile energy and the plasma temperature with all important mechanisms considered in detail. The relevant results are found to be quite different from those of an α particle or a proton. One important reason for this is the rapid increasing of the charge state of a Ga ion at plasma temperature. This reason also leads to the inelastic stopping which does not always decrease with the increase of plasma temperature, unlike the case of an α particle. The nuclear stopping becomes very important at high enough plasma temperature due to the heavy reduced mass of a Ga and an Au ion and the above-mentioned reason. The well-known binary collision model [Phys. Rev. 126 (1962) 1] and its revised one [Phys. Rev. A 29 (1984) 2145] are not working or unsatisfactory in this case.

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Keywords: Energy loss; Hot Au plasma; Ga ion

1. Introduction

With the development of fusion science, especially the ion-driven inertial confinement fusion [1] and fast ignition [2], the stopping power in plasmas has become a hot topic [3]. The stopping data of various ion beams in the plasmas of different materials is necessary for the fusion research. Besides DT, some other materials such as C, Be and Au are often used in the design of fusion targets [4,5] or fusion devices of fast ignition driven by ions [2,6]. During the implosion process, these materials will mix with DT fuel inevitably, which will affect the heating of DT ions. In recent years, the fuel with heavy elements Pu and U is under consideration in the controlled fusion experiments [7]. Usually the heavy element materials such as Au, U and Pu are hard to be fully ionized even at very high temperature. In inertial confinement fusion driven by energetic ion beams, various species of ions from low to high Z elements are possible candidates of the driven beam [2,6]. So far, there were some experiments about the energy loss of lots of particles from light to heavy ions [8] in plasmas. In recent year such experiments for highly-charged Ar ions [9] and fully-ionized He ions [10] were made in GSI Helmholtzzentrum für Schwerionenforschung (GSI) and Institute of Modern Physics (IMP) in Lanzhou, respectively.

Generally speaking, there are three main mechanisms for the slowing down of heavy particles in fully-ionized plasmas. The first one is the close collision [11] between the projectile and the free electron; the second one is the friction-like force caused by plasma polarization due to the projectile moving in the plasmas, which belongs to the distant collision [11]. Hereafter we call them as the plasma electronic stopping. The last one is the nuclear stopping [12,13], which is the elastic scattering of particle beams with the target nuclei. For partially-ionized plasmas, especially the hot high-Z plasmas, most electrons are populated in excited or ionized states and the energy for excitation or ionization will be influenced by

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the plasma effects due to the existence of the free electron background. In this case, all the possible inelastic collisions between the projectile and electrons also slow down the projectile, which makes the related calculation much more complex.

Recently we proposed an *ab initio* model [14] to estimate the stopping power of α particles in hot dense Au plasmas. In this model, the main mechanisms of the slowing down were considered with all the possible inelastic processes calculated completely. Last year the nuclear stopping of protons in Au plasmas [15] was investigated and reasonable results were found basing on the reliable potential and the velocity distribution of an Au ion. Since various ions from low to high Z materials are possible candidates of the driven beam, the energy loss of heavy ions in plasmas is important for fusion study. As far as we know, the investigation in this respect is far from enough, let alone the detailed research with all the main mechanisms considered. Moreover, the energy loss of such ions should be quite different from that of light ions due to their high charge states and heavy mass. In the present work we take the example of a Ga ion in hot Au plasmas to investigate this problem.

Since the charge state of a Ga ion in hot plasmas is very high, the coupling of the ion with the plasma is strong, which means that the non-perturbative calculation should be applicable. Here the contributions from plasma electronic stopping and nuclear stopping will be made according to the non-perturbative methods in Refs. [16] and [15], respectively. For inelastic stopping, our previous method in Ref. [13] will still be used since it is valid for high projectile energy, meanwhile its contribution is usually much smaller than others at low projectile energy. For conciseness, these methods will not be introduced here as well as the average atom model [17,18] although they are the basis of our calculation.

The paper is organized as follows. In Section 2, the effective charge state of a Ga ion in hot plasmas which is important to the calculation of energy loss will be presented. Section 3 is devoted to the nuclear stopping. In Section 4 the contributions of all the inelastic processes to energy loss are given and Section 5 is devoted to the investigation of the plasma electronic stopping. In Section 6 the total results of energy loss is obtained, based on which the role of each mechanism is analyzed. Finally some conclusions are drawn in Section 7. In these sections almost all the relevant results will be compared with those of proton or alpha particle incidences, and some explanations are given for the differences of the results from different projectiles. Similar results or behaviors found in our previous work [14,15] will not be repeated in the present work. Atomic units ($e = m_e = \hbar = 1$) are used in this work unless otherwise explicitly indicated.

2. Charge state for a Ga ion in plasmas

The recombination and charge transfer may occur especially for highly charged projectile, which will alter the charge state of the projectile. Therefore it is necessary to consider the charge state correction of a Ga ion in the plasmas since the nuclear charge Z_p is high enough. The method in Ref. [1] was used to make the correction in the present work. In the following sections Z_p will be replaced by the effective charge Z_{eff} with $Z_{eff} = Z_p\gamma$, where $\gamma = 1 - 1.041\ \exp[-0.851 <|v_p - v_e|>^{0.847}/Z_p^{0.432}]$. Here $<|v_p - v_e|>$ is the average relative velocity between a Ga ion and free electrons in the plasmas. Fig. 1 plots γ for different projectile energy E_p where the Maxwellian velocity distribution of the free electrons in the plasmas at different temperature (T_e) is assumed. Clearly γ rises up with temperature and becomes close to 1.0 when T_e is 5 keV. In addition, γ rises up rapidly for high enough E_p when $T_e \leqq 400$ eV.

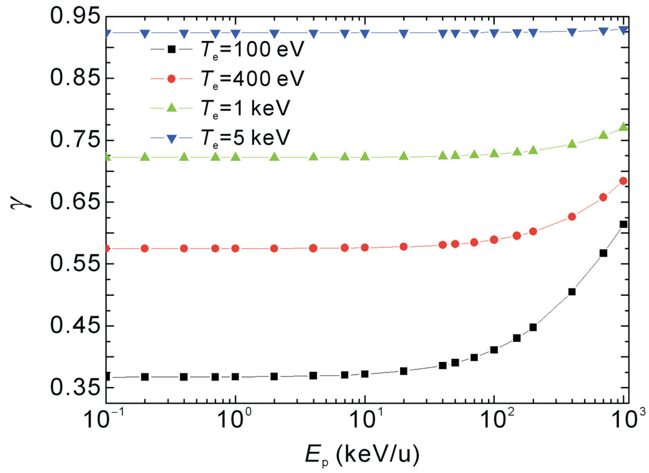

Fig. 1. Effective charge state of a Ga ion as a function of E_p in hot plasmas at different T_e with Maxwellian velocity distribution of free electrons considered.

3. Nuclear stopping

By means of the Au ion potential from the ionic sphere model [17,18] and the method in [15] the nuclear stopping of a Ga ion in hot Au plasmas can be estimated and the relevant results are plotted in Fig. 2(a) and (b), where the densities for Au plasmas ρ_{Au} are equal to 19.3 and 1.93 g/cm^3, respectively. Here the different curves denote the results at different T_e and the corresponding values of the ionization degree Q of Au ions are marked. Apparently all the results have the same feature that they turn from negative to positive with E_p around T_e, then rise up rapidly with E_p and finally decrease to zero gradually. Besides, they decline rapidly with E_p decreasing when $E_p < T_e$. Moreover, the results rely on the plasma density when $E_p \geq T_e$ by comparing Fig. 2(a) with (b). All these characteristics can be found in Ref. [15] where the relevant reasons have been given.

Deeper understanding will be obtained if the comparison is made with the results in Ref. [15] with a proton incidence. In the present work, the maximum of the nuclear stopping always rises up with T_e for the same plasma density. However, the maximum at $T_e = 5$ keV is smaller than that at $T_e = 1$ keV with the same density according to Fig. 1 in Ref. [15]. This is because the charge state of a Ga ion increases with the temperature rapidly, which results in the stronger interaction

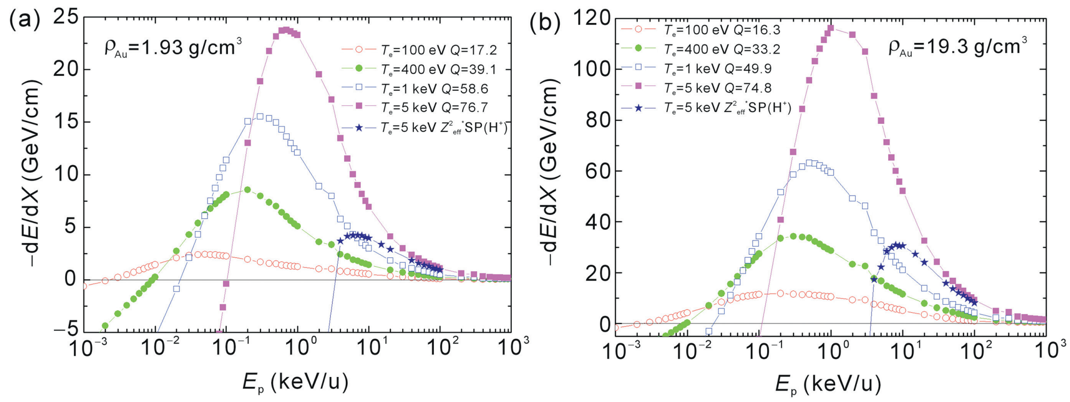

Fig. 2. Nuclear stopping in Au plasmas at (a) $\rho_{Au} = 1.93$ g/cm^3 and (b) $\rho_{Au} = 19.3$ g/cm^3 with different curves denoting at different temperatures. The values of Q are marked for the ionization degree of Au ions with different densities and T_e, which are obtained by the ionic sphere model [17,18]. For the curves with squares and circles, the projectile is Ga ions. For the curves with stars, the projectile is protons with the results multiplied by $(Z_{eff})^2$.

between the projectile and the target ion at higher T_e while the charge state of protons as the projectile is a constant. Fig. 2 also indicates that the energy loss of protons is much smaller than that of a Ga ion even if it is multiplied by $(Z_{eff})^2$. This is easy to see if we notice the fact that the reduced masses of a Ga and an Au ion are much heavier than those of proton and Au ions, which makes it much easier for Au to get energy from energetic Ga ions than from protons. Here the reduced mass of the projectile and the target ion is defined as $M_p M_t/(M_p + M_t)$, where M_p and M_t are the masses of the projectile and the target ion, respectively. According to Eq. (1) in Ref. [15], the different reduced masses would result in different deflection angles in the frame of the mass center for the same impact parameter. This affects the energy exchange in the binary collision, which leads to a different result of energy loss. Usually both Z_{eff} and the reduced mass have strong influence upon the nuclear stopping.

It is well-known that the binary collision model [19] based on the Coulomb potential with the cutoff of force range is extensively used to estimate the energy loss in plasmas. In the model, a constant Coulomb logarithm is given whose argument is chosen as $\Lambda_c = \frac{3}{2Z_p Q}\left(\frac{T_e^3}{\pi n_e}\right)^{1/2} = \frac{3T_e\lambda_{De}}{Z_p Q}$. Here λ_{De} is defined as $\sqrt{T_e/4\pi n_e}$ with n_e being the density of free electron in the plasmas. Our previous work suggested that this model could not describe the nuclear stopping of protons in hot Au plasmas. In the present work it is found that this conclusion is still valid for Ga ion incidence. But the reason is different if we notice that $\Lambda_c < 1$ due to the high charge state of a Ga ion, which makes the model fail completely.

We notice that many years ago Ferrariis and Arista [20] discussed the revision of the above-mentioned model by introducing Λ_q, which is dependent upon the relative velocity between the projectile and the target ion. In addition, the binary collision under the Debye potential instead of the Coulomb one was proposed in Ref. [21]. Here it is worthy to compare these models with ours for the case of a Ga ion in hot Au plasmas. All the relevant results from these models are plotted in Fig. 3 at $T_e = 1$ keV. It is easy to see that at high enough E_p these results are close to each other. For low E_p, the result by Ferrariis and Arista's model (FAM) is negative with E_p between 0.01 and 0.045 keV/u when $\rho_{Au} = 1.93$ g/cm^3 and between 0.01 and 0.1 keV/u when $\rho_{Au} = 19.3$ g/cm^3. Meanwhile in most range of such E_p, the nuclear stopping from our model is positive. In addition, the result from FAM becomes positive and rapidly rises up with E_p decreasing when $E_p < 0.01$ keV. Apparently this behavior is unreasonable and the nuclear stopping should always decline with E_p decreasing once it is negative. We think that such a behavior in the model originates from the approximations in looking for an analytical expression. Therefore the simple Coulomb potential with the force range of Debye length cut-off can not describe the interaction between the projectile and the target ion in this case. The Debye potential model is much better than FAM since its behavior is similar to ours and thus obtained the turning point for the nuclear stopping from negative to positive, which is closer to our model (as indicated in Fig. 3). However, the difference for the results between the Debye potential model and ours are still obvious due to the quite different potentials used in these two models.

In summary, by means of the potential from the ionic sphere model, the nuclear stopping of a Ga ion in hot Au plasmas is calculated and compared with that of proton incidence. The heating of the plasma will be stopped when a Ga ion slows down to the energy nearly below T_e. The maximum of the nuclear stopping rises up with T_e at fixed plasma density, which is different from that of proton incidence due to the huge difference of their masses and charge states. In addition, the well known binary collision model [19] based on the Coulomb potential fails to describe the nuclear stopping in this case. Moreover, the model revised by Ferrariis and Arista [20] is found to be inappropriate for this case. Although the result from Debye potential is improved a lot, the difference between the model and ours is still obvious due to the quite different potentials used in these two models.

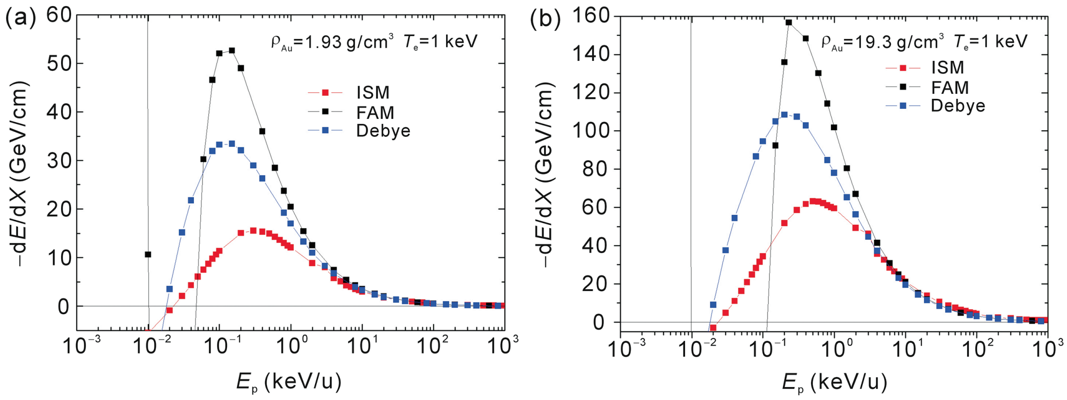

Fig. 3. Nuclear stopping for a Ga ion moving in Au plasmas with $T_e = 1$ keV at (a) $\rho_{Au} = 1.93$ g/cm^3 and (b) $\rho_{Au} = 19.3$ g/cm^3 in different models. ISM, FAM and Debye denote the results for our model, the Ferrariis and Arista's model [20], and Debye potential model [21], respectively.

4. Energy loss due to inelastic processes

Inelastic processes have important influence upon the energy loss in partially ionized plasmas. In this section the investigation related to the inelastic stopping will be made and the relevant results will be presented.

The detail to calculate the inelastic stopping in our model has been described in our previous work [14] and here only a brief introduction of the model is presented. In our model, the relativistic plane Born approximation [22] is used although it's not quite good when E_p is close to the transition energy of the electron (ΔE). All the possible transition channels between different energy states should be considered, including all the bound states and the free states since the projectile will lose its energy if it makes the electron jump to a higher energy level by the collision with the electron, and vice versa. In the calculation the electron occupation numbers in different states are considered and the final results are obtained by the summation over the contributions of all the calculated transitions. For free electrons, the maximum energy is chosen as 82.2 (in atomic unit) and the energy interval, which is usually below 0.5, may be below 0.1 for certain energy in order to get reliable and convergent results.

Fig. 4 shows our results of inelastic stopping as a function of E_p with $\rho_{Au} = 19.3$ g/cm^3 due to all the excitations and deexcitations (a) and all the ionizations and its reverse processes (b). Both Fig. 4(a) and (b) indicate that generally speaking, the contribution from these processes becomes more and more important with temperature decreasing, and vice versa. This behavior is similar with the case of an α particle incidence [14], where its explanation has been given. However, there are some differences from that case which should be noticed. This first one is that the result in Fig. 4(a) for $T_e = 400$ eV becomes bigger than that for $T_e = 100$ eV. The second one is that the difference among the results in different T_e is much smaller than that for an α particle incidence. These are not difficult to understand if the fact that the rapid increasing of the charge state for a Ga ion with T_e instead of the unchanged charge state for an α particle is considered.

It should be noted that the collisional-radiative model is often used to describe the evolution of the occupation number of electrons at each energy level due to all the inelastic processes caused by the photons, electrons and ions. In our method, the average occupation number for the target ion is obtained by ionic sphere model. In order to get energy loss, the inelastic stopping caused by the projectile is concerned instead of the change of the occupation number caused by the inelastic processes. Hence, the collisional-radiative model is not necessary to describe the inelastic stopping.

5. Plasma electronic stopping

Besides the inelastic stopping, the plasma electronic stopping is also important to the slowing down of the projectile. Due to the strong coupling of a Ga ion with free electrons, the non-perturbative calculation is adopted here according to Ref. [16]. In our calculation, the combined formula in Ref. [16] is used with $v_{max} = 5v_{the}$ chosen as suggested in that work, where v_{the} is the thermal velocity of free electron $\sqrt{T_e}$. Fig. 5 plots the relevant results as a function of E_p at different T_e with $\rho_{Au} = 19.3$ g/cm^3.

Fig. 5 suggests that although the charge state of a Ga ion rapidly increase with T_e, the plasma electronic stopping rises up almost with T_e decreasing just as the case of an α particle incidence, which is not shown here. We think that there are two reasons responsible for this. The first one is that the scaling law of the stopping in the case of high Z_{eff} should be $Z_{eff}^{3/2}$ instead of Z_{eff}^2, where the latter is valid for very low Z_{eff} or Z_p. Another is related with the effect of the friction-like force caused by plasma polarization, which has a scaling of Z_{eff}^2 [23,24]. This effect is greatly suppressed due to the increase of v_{the} with T_e according to the combined formula in Ref. [16].

6. Total results of energy loss and role of each mechanism

So far, the contributions of all the important mechanisms to the energy loss have been discussed in detail for a Ga ion moving in hot Au plasmas. In order to see the role of each

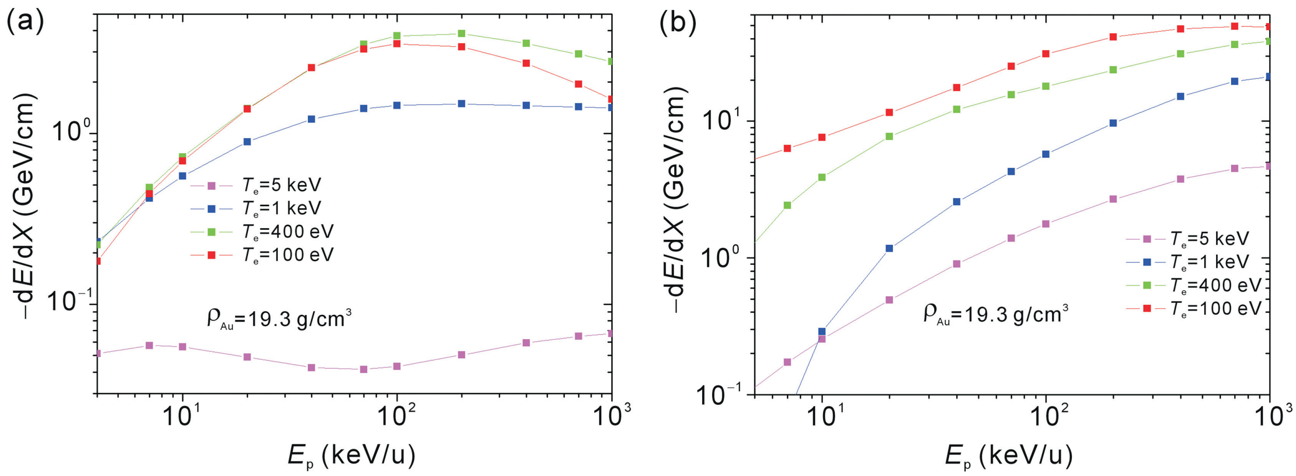

Fig. 4. Inelastic stopping as a function of E_p due to (a) all the excitations and de-excitations and (b) all the ionizations and its reverse processes at $\rho_{Au} = 19.3$ g/cm^3.

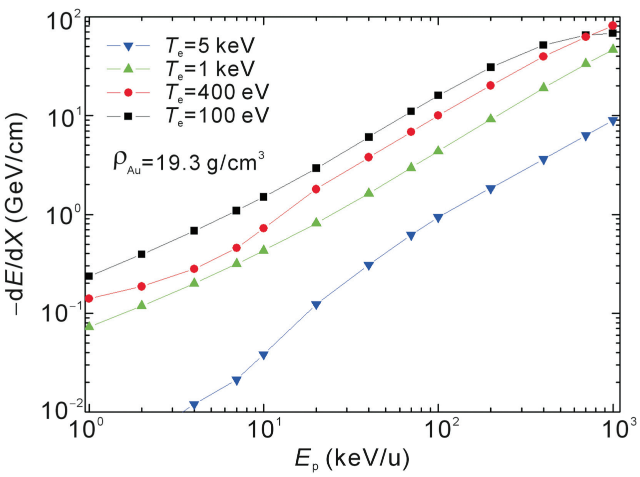

Fig. 5. Plasma electronic stopping as a function of E_p at different T_e with $\rho_{Au} = 19.3$ g/cm^3.

mechanism playing in the total result, the energy loss due to different mechanisms need to be put together for comparison, where the total inelastic stopping is found by the summation over all the inelastic contributions. In our calculation, all the results have been calculated at different T_e with $\rho_{Au} = 19.3$ g/cm^3 for both a Ga ion and an α particle incidence. The relevant results at $T_e = 1$ keV is shown as Fig. 6, which tells us that different mechanism plays the role in different energy range and all the mechanisms need to be considered in order to get a reliable overall result. It is easy to see that in the case of a Ga ion, the nuclear stopping is very strong and plays an important role in a wide range of E_p, which is quite different from the case of an α particle. In addition, the plasma electronic stopping becomes as important as the inelastic one in Fig. 6(a), which is different from that in Fig. 6(b). The reasons of these have been presented in the previous sections and will not be repeated here.

According to the above results, we can study the contribution of each stopping mechanism to the total energy loss when the projectile slows down in the plasma from the initial

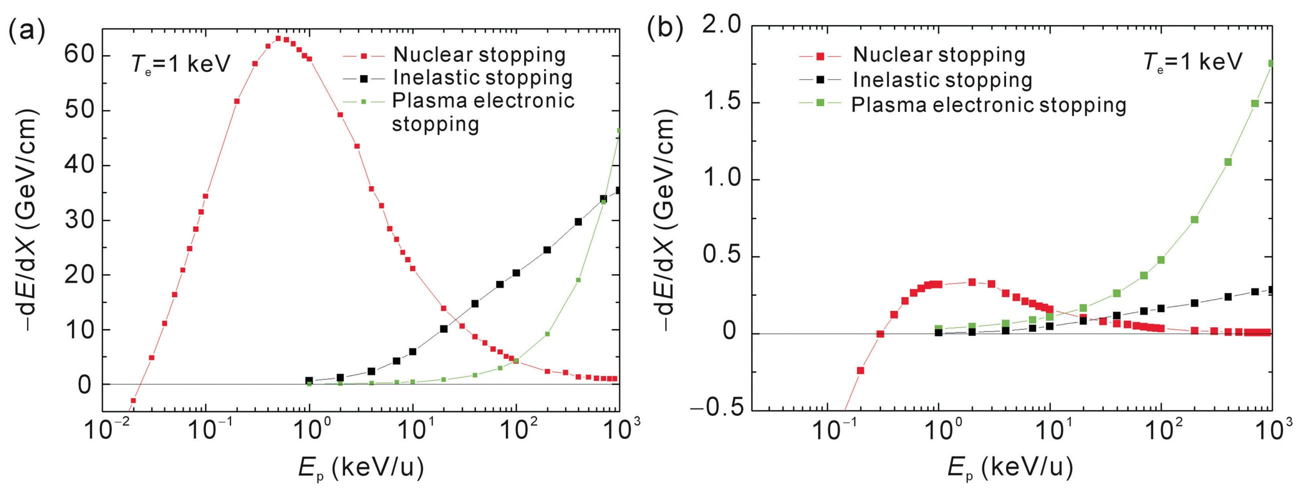

Fig. 6. Energy loss in Au plasmas with solid density as a function of E_p at $T_e = 1$ keV due to different mechanisms for the projectile of (a) a Ga ion and (b) an α particle. The inelastic stopping is the sum of all the inelastic contributions which include excitation, ionization and their reverse processes.

Table 1
Fraction of the contribution of each mechanism to the total energy loss at different T_e with $\rho_{Au} = 19.3$ g/cm^3 for the slowing down of a Ga ion and an α particle. Here the fraction is multiplied by 100. NS, IS, and PES denote the nuclear stopping, inelastic stopping and plasma electronic stopping, respectively.

Mechanism	$T_e = 0.1$ keV		$T_e = 0.4$ keV		$T_e = 1.0$ keV		$T_e = 5.0$ keV	
	Ga	α	Ga	α	Ga	α	Ga	α
NS	1.37	0.38	2.76	1.10	6.81	2.42	32.0	9.14
IS	57.12	33.26	58.18	18.3	51.5	14.0	32.7	12.96
PES	41.5	66.35	41.0	80.6	41.7	83.58	32.3	77.9

energy E_0 to the energy in equilibrium with T_e. In the present work, E_0 is chosen as 1 MeV/u. The energy loss due to the nuclear stopping is $\Delta E_{NS} = \int_{T_e}^{E_0} \frac{dE_{NS}}{dx}\left(\frac{dE_{NS}}{dx} + \frac{dE_{IS}}{dx} + \frac{dE_{PES}}{dx}\right)^{-1} dE$, where NS, IS, and PES denote the nuclear stopping, inelastic stopping and plasma electronic stopping, respectively. $\Delta E_{NS}/(E_0 - T_e)$ is the fraction of the contribution of nuclear stopping to the total energy loss, which is just the factor of ion-electron energy partition in the plasmas. The fraction for other mechanism can be found in the same way, and all the fractions at $\rho_{Au} = 19.3$ g/cm^3 are presented in Table 1 for both Ga ion and α particle incidences.

According to Table 1, the fraction from nuclear stopping which is related to the energy transferred to Au ions, increases rapidly with T_e for both cases. This is consistent with the increase of ionization degree of Au with T_e. The part of energy obtained by an Au ion from an α particle is 9.14% at $T_e = 5$ keV. Meanwhile the corresponding result from a Ga ion is 32.0%, which is very high. The part of energy obtained by an Au ion from a Ga ion is apparently higher than that from an α particle, which is obviously closely related to the heavier reduced mass of a Ga and an Au ion than that of an α particle and an Au ion.

As for the fraction from inelastic stopping, it rapidly decreases with T_e according to Table 1, and the fraction from plasma electronic stopping is always the most important in the case of an α particle, which have been discussed in our previous work [14]. These results are different from the case of a Ga ion, where the fraction from plasma electronic stopping is not the most important one. Part of the reason has been given in Section 6.

Here it should be mentioned that in the actual experiment, a particle beam or a cluster is used to heat the plasma. In the present work, the energy loss of one ion was studied. For a particle beam or a cluster [25] the correlation among the beam ions makes the energy loss of beam ions different from that of one ion, especially for the plasma electronic stopping. The related influence will be studied in the future.

7. Conclusions

In summary, we have studied the energy loss of an energetic Ga ion moving in hot Au plasmas with the main mechanisms considered and compared with that of an α particle or a proton. The following conclusions can be drawn:

(1) Different mechanisms are found to play their roles in different energy ranges and all the mechanisms need to be considered in order to get the reliable data of energy loss.
(2) With the increase of T_e, nuclear stopping of a Ga ion in hot Au plasmas becomes more important than that of an α particle. That is closely related with the heavier reduced mass of a Ga and an Au ion than that of an α particle and an Au ion. It makes the fraction of the energy obtained by an Au ion from a Ga ion as high as 32.0% at $T_e = 5$ keV and $\rho_{Au} = 19.3$ g/cm^3 for $E_p = 1$ MeV/u.
(3) The reasonable behavior of nuclear stopping for a Ga ion in hot Au plasmas can be obtained both by the ionic sphere potential and the Debye potential although their results are obviously different. The models in the Coulomb potential with the force range cutoff of Debye length are found not working or to be unsatisfactory in this case.
(4) The inelastic stopping of a Ga ion in hot Au plasmas does not always increase with T_e decreasing, and the difference among the results at different T_e for a Ga ion incidence is much smaller than that for an α particle. These are mainly attributed to the rapid increase of the charge state of a Ga ion with T_e.
(5) The energy loss of a Ga ion in hot Au plasmas obeys $Z_{eff}^{3/2}$ scaling instead of Z_{eff}^2, and the effect of the friction-like force caused by plasma polarization is greatly suppressed due to the increase of v_{the} with T_e. This is highly related to the reduction of the plasma electronic stopping almost with T_e just as the case of an α particle incidence, although the charge state of a Ga ion increase rapidly with T_e.

Acknowledgments

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