

ATOMIC PROCESSES AT THE END OF THE RANGE OF FAST IONS IN PLASMA

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Experiments in which various ions are stopped in low density hydrogen plasmas are used in several laboratories in order to study stopping power and charge state problems. This work suggests that in existing experimental systems the parameters can be chosen such that the end of the range will occur inside the plasma column. The charge state and level populations of ion projectiles in hydrogen plasma are calculated. The predicted narrow region over which recombination occurs can be used to check stopping power theory and to directly measure the range using spectroscopic diagnostics. The feasibility of such an experiment is examined.

1 INTRODUCTION

The physics of energy deposition by fast ions in plasma is one of the central problems in ion beam inertial confinement fusion. A very wide range of parameters occur in ICF targets during the deposition process, from the initial state of cold solid to the final state of low-density, high-temperature plasma. The energy deposition profiles in plasma are expected to differ drastically from those in the better-known case of cold matter for two reasons: the stopping power of plasma is different from that of cold matter even for a given fast-ions charge^{1,2}; and the charge of an ion moving in a plasma is different.^{3,4} Experimental results on the stopping of light and heavy ions in plasma are still scarce^{5–9}.

In existing experiments on heavy ion stopping^{7–9} an accelerator beam and a discharge plasma are employed. The energy loss and charge state of the ions are determined after exit from the plasma column. In order to avoid the issue of the relation between the charge after exit from the target and the charge relevant for stopping^{10,11} it is desirable to choose the parameters such that the end of the range will occur inside the plasma column. Also, any direct information on the state of the projectile ion will shed light on the interaction processes. In-flight spectroscopy of the projectile ions in the plasma could be very useful for this purpose. It is the object of this work to examine the feasibility of such an experiment.

At available plasma-column densities, stopping the ions inside the plasma requires using lower ion energies than those delivered by the accelerators in existing systems^{7–9}. If this is achieved, it is then possible to choose the projectile species and energy such that recombination into the levels which produce the desirable lines for diagnostics occurs sharply at the end of the range. This will mark the end of the

range and will produce a narrow region with relatively high emission intensity. Such a situation is possible because the ions are highly stripped when they are fast, and then recombination of the free plasma electrons is inefficient. Capture processes only become efficient when the ion velocity is not high compared with the thermal velocity of the plasma electrons.

It would facilitate such an experiment if existing experimental systems⁸, employing tandem accelerators that provide ions at higher energies than those required here, could still be used by placing a moderating foil in the beam path. In the following we check this point by studying the degradation of beam quality by such a foil.

A fully stripped hydrogen plasma is assumed, at a temperature of 2 eV and densities of $4 \times 10^{17} \text{ cm}^{-3}$ and $1 \times 10^{18} \text{ cm}^{-3}$. Carbon ions at an energy of 2 MeV and 4 MeV can be stopped inside such available plasma columns, respectively.

2 ATOMIC MODELS

The level populations and charge state of the ion have to be calculated dynamically and self-consistently with the ion velocity as it is slowed down in the plasma³. These are determined by the balance among the various excitation, de-excitation, ionization and capture processes. In the calculations we have considered the following processes: collisional excitation and de-excitation, collisional ionization, radiative decay, radiative recombination, three-body recombination, and dielectronic recombination.

For the purpose of this feasibility study, an average ion model¹² was used for the description of the projectile, and only the principal quantum numbers n were considered in characterizing the ionic levels. While for real spectroscopic applications more-detailed atomic models with detailed configuration accounting are needed, this simplified and computationally simple atomic model should suffice for our purpose.

The binding energies in the projectile were calculated consistently with the ionization and excitation states using the ionic screening model¹².

The velocity distribution of the plasma electrons in the frame of the projectile were taken into account in calculating the various rates.

The required oscillator strengths were calculated in the hydrogenic model¹³.

Collisional excitation by the plasma electrons is calculated following Van Regemorter¹⁴. Deexcitation was calculated following Vriens and Smeets¹⁵. Excitation and de-excitation by collisions with plasma ions were similarly calculated.

The cross-sections for collisional ionization by plasma electrons were calculated according to Lotz¹⁶. Collisional ionization by plasma ions was calculated in the binary encounter approximation^{17,18} with the binding and Coulomb deflection corrections¹⁹ for slow collisions.

Radiative decay between levels was calculated following Mertz *et al.*²⁰. Radiative recombination and three body recombination were calculated according to Zeldovich and Raizer¹³.

Dielectronic recombination was determined according to the following considerations: The charge state of the projectile is calculated to be $Z = 4$ all the way from close to its injection point down to an energy of ~ 0.2 MeV, where recombination

starts to dominate. At $Z = 4$ the ions are in the $1s^2$ state. The reason for that is as follows: At our injection energy (2–4 MeV) the kinetic energy is sufficient to collisionally ionize all $n = 2$ electrons very quickly. This does not depend on the initial charge state at injection. On the other hand, the energy is not sufficient to ionize or excite the K -shell electrons. Also, recombination processes are too inefficient to populate higher levels as long as ion is fast. At this stage dielectronic recombination is inefficient because of the high excitation energy required for the process to occur (i.e., the $1s$ to $2p$ transition). For C^{3+} ions, which appear at lower energies, the data of Griffin *et al.*²¹ are used for the dielectronic recombination accompanied by the $1s^2 2s$ to $1s^2 2p$ transition. The captured electrons were assumed to populate the $n = 3$ and $n = 4$ levels. For C^{2+} ions the scheme of Burgess²² as quoted by Post *et al.*²³ was used, with the excitation $2s2p$ to $2p^2$ (singlet).

The charge state and level populations were calculated by integrating the coupled rate equations. The calculated charge state is used to calculate the stopping and thus a self consistent calculation following the history of the projectile is obtained.

3 THE MODERATING FOIL

In existing experimental systems⁸ the beam source is a tandem accelerator, which produces ions at much higher energies than the 2–4 MeV required for the experiment proposed here. It would be very appealing if the existing accelerator–plasma source systems could still be used. A simple means to lower the ion energy in these systems could be the use of a moderator foil placed in the beam path. However the drastic drop in energy which is required (from 20 MeV to 2 MeV) could be accompanied by a drastic degradation in beam quality due to straggling and scattering.

We used Monte Carlo techniques in order to estimate these effects. In the calculations a 24 MeV carbon beam was assumed. The moderating foil was 3.9 mg/cm^2 carbon at a density of 1 g/cm^3 . At this thickness the carbon ions are slowed to approximately 3 MeV. Degradation effects were evaluated by following Monte Carlo histories of test projectiles.

Multiple scattering was calculated using Moliere's theory²⁴. It was found that under the conditions of the present problem this is not a major factor in the degradation of beam quality, and does not significantly affect the exit energy distribution.

In evaluating the effects of energy straggling and charge state fluctuations the following procedure was applied. At the beginning of each step in the history of a test projectile the cross-sections for ionization and capture were calculated using the methods described in Ref. 4. The distance for this step is then determined as a fraction of the mean free path for the more probable process. The Monte Carlo procedure is then applied in order to determine the change in charge state due to both loss and capture. The mean energy loss in this step is then calculated using the methods of Ref. 4. Straggling effects are then added by a Monte Carlo selection of an energy change from a distribution according to the simplified theory of Lindhard and Scharff²⁵.

4 RESULTS AND DISCUSSION

We present results for the stopping of carbon ions injected at an energy of 2 MeV into a plasma at a temperature of 2 eV and a density of $4 \times 10^{17} \text{ cm}^{-3}$, and ions of 4 MeV injected into a plasma at the same temperature and a density of 10^{18} cm^{-3} .

Ions injected with charge $Z = 2$ reach the state $Z = 4$ very quickly close to the injection point. This charge state is maintained along the ion path until it is slowed down to an energy of $\sim 0.2 \text{ MeV}$. At this stage the configuration is $1 s^2$. As the energy drops further, higher shells start to be populated. The charge state of the ions as function of distance into the plasma is shown in Figures 1 and 2. It is evident from the figures that once recombination processes become active at low projectile energy, recombination occurs sharply over the short distance of a few millimeters. For comparison we show in Figure 3 the charge state as function of distance according to the usual equilibrium cold matter formula²⁶. This demonstrates the strong plasma effects on the stopping processes.

The sensitivity of the results to uncertainties in the cross-sections was checked by multiplying the cross-sections for dielectronic recombination by a factor of 10, which resulted in no significant change. The expected uncertainties in the various cross-sections will have only a small effect on the conclusion explained above that the charge state remains nearly constant along the high energy part of the projectile path.

Calculated results for the possible effect of a moderating foil are shown in Figures 4 and 5. In Figure 4 we show the energy distribution of the ions due to both energy

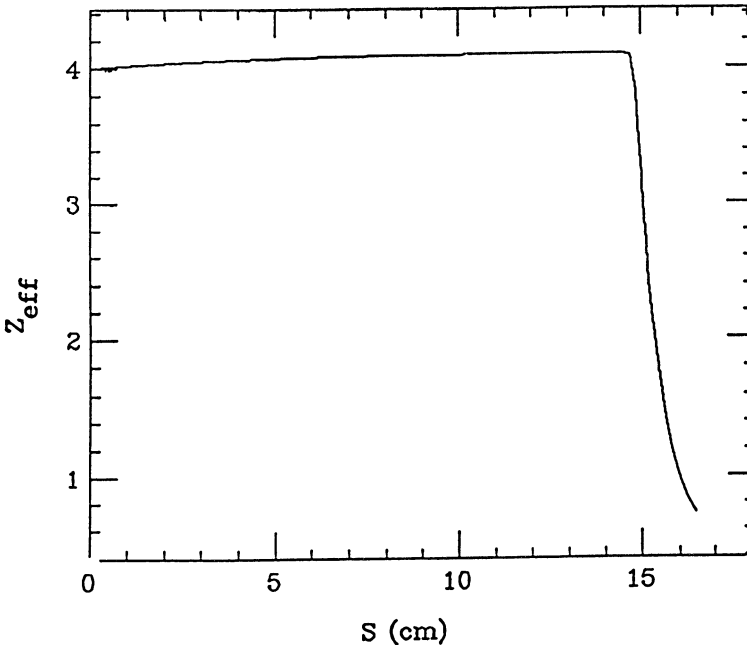


FIGURE 1 The charge state of a carbon projectile at initial energy of 2 MeV as function of distance in a hydrogen plasma at density $4 \times 10^{17} \text{ cm}^{-3}$ and temperature 2 eV.

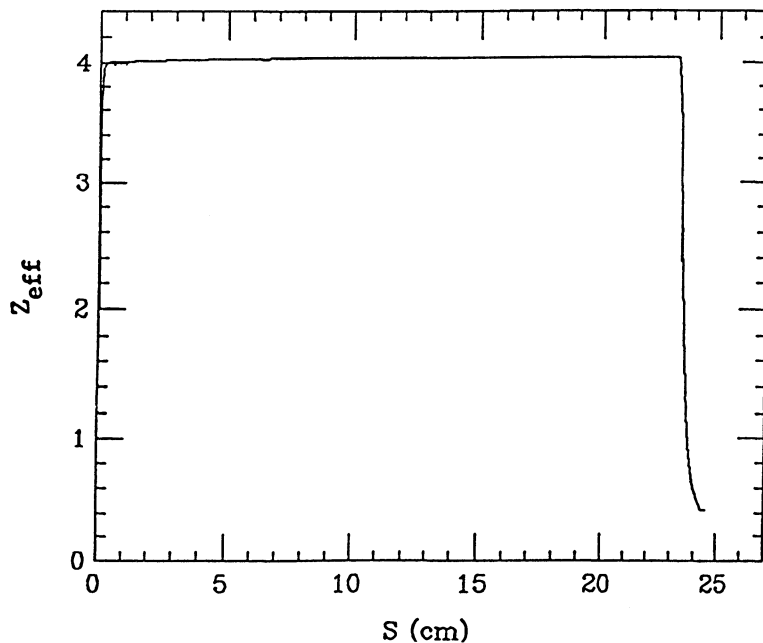


FIGURE 2 The charge state of a carbon projectile at initial energy 4 MeV as function of distance in a hydrogen plasma at density 10^{18} cm^{-3} and temperature 2 eV.

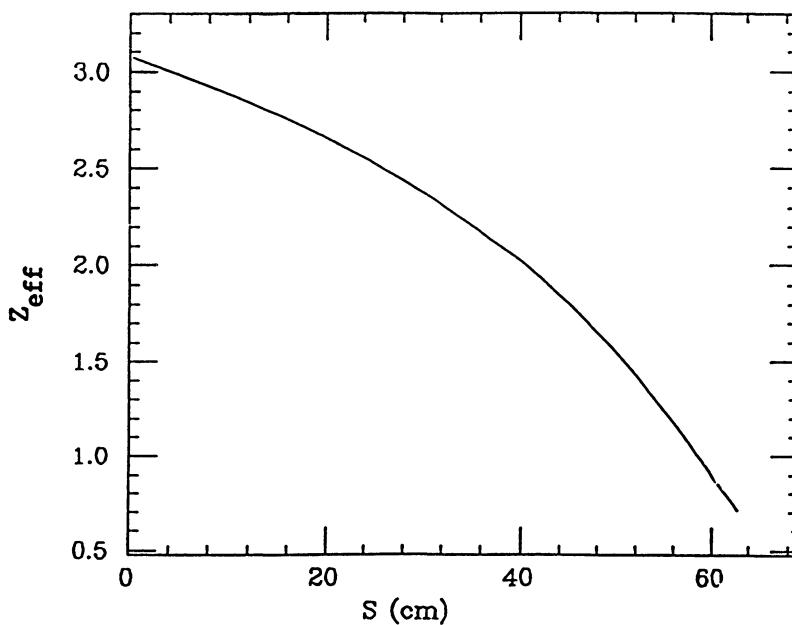


FIGURE 3 The charge state of a carbon projectile as function of distance calculated as in cold matter equilibrium. Parameters are as in Figure 1.

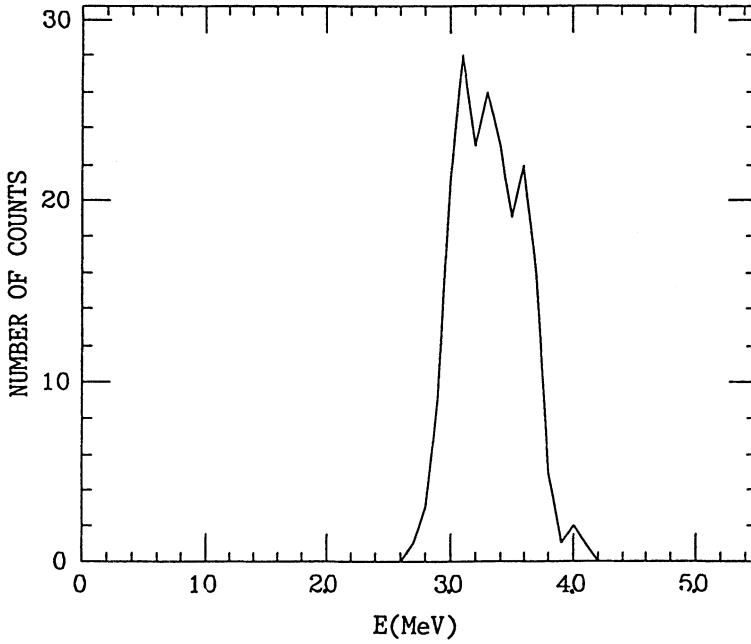


FIGURE 4 Energy distribution due to energy straggling and charge state fluctuations of a 24 MeV carbon beam passing through a 3.9 mg/cm² carbon foil.

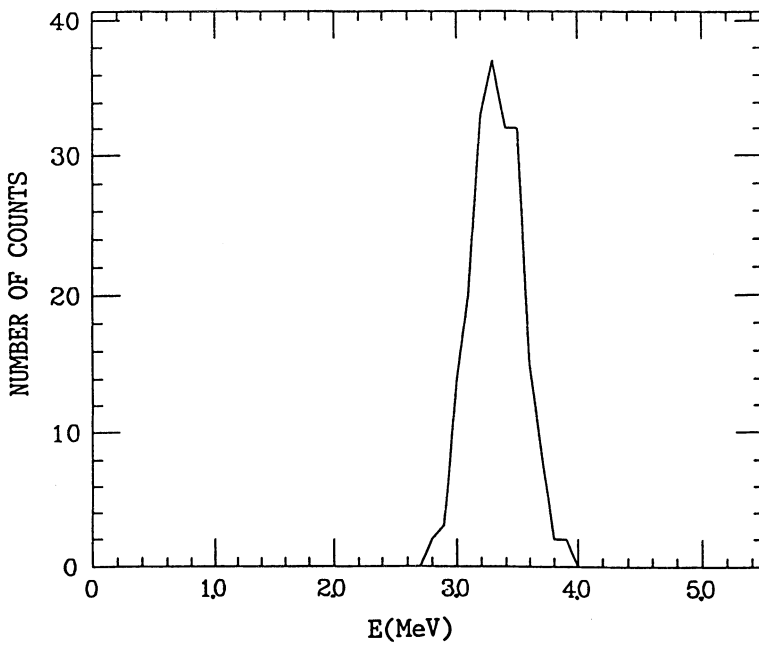


FIGURE 5 Energy distribution due to charge state fluctuations alone. Parameters as in Figure 4.

stragglings and charge state fluctuations with the beam and foil parameters given above. In Figure 5 we show the contribution of charge fluctuations alone to the effect. The total broadening of the energy distribution (~ 1 MeV) is very significant; it was checked in a calculation that varying the injection energy from 4 MeV to 3.5 MeV will shorten the range in a 10^{18} cm $^{-3}$ plasma by as much as 5 cm. This may rule out the use of moderating foils, and might make it necessary to employ a low energy accelerator as beam source.

5 PROPOSED DIAGNOSTICS

The characteristic charge state profile of Figures 1 and 2 can be used for a direct measurement of ions range in the plasma, provided that a reasonably monoenergetic ion source is used. Spectroscopic diagnostics can be employed using the high concentration of recombining ions at the end of the range (C^{2+} , C^{3+}). In particular, the transition $2s2p-2p^2$ ($1P^0-1D$) in C^{2+} at 2296.89 Å could be a convenient choice²⁷. In order to evaluate the feasibility of such a measurement we performed a preliminary calculation of the intensity of this line when a C^{3+} ion in its ground state is placed in a hydrogen plasma at rest. A dynamic non-equilibrium collisional-radiative code²⁸ was employed. The results indicate that in a 10^{18} cm $^{-3}$ plasma $\sim 10^{-3}$ photons per recombining ion will be emitted, and a higher intensity is expected for a 4×10^{17} cm $^{-3}$ plasma. In available experimental systems⁸ beam currents of $\sim 10^{-6}$ A and plasma lifetimes of ~ 1 μ s are expected. Under such conditions the use of interference filter diagnostics could make a measurement feasible.

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