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JOURNAL DE PHYSIQUE
Colloque C8, supplément au n°11, Tome 44, novembre 1983 page C8-149

AB INITIO CALCULATIONS OF THE CHARGE STATE OF A FAST HEAVY ION STOPPING IN A FINITE TEMPERATURE TARGET*

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RESUME

On présente un calcul de l'état de charge dépendant du temps d'un ion lourd traversant une cible à température finie. Les équations d'évolution sont intégrées à l'aide d'un modèle d'atome moyen.

ABSTRACT

We present a calculation of the time dependent charge state of a heavy projectile traversing a finite temperature target. The calculation uses an average-atom model to integrate the rate equations.

As a result of a recent interest in heavy-ion driven ICF targets, we are improving the stopping power calculations used in the simulation codes for target design. Knowing the effective charge of the projectile ion is very important for this since the stopping power is proportional to the square of the effective charge. Because of the extreme conditions of heavy-ion irradiation (a very heavy projectile at very high velocity enters the target in a low charge state), we are concerned that the effective charge may significantly differ from the usual equilibrium charge state. This article discusses an approximate calculation of the charge state of a fast, heavy-ion traversing a finite temperature target plasma.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

To perform this calculation, we use an average atom model for the projectile ion[1] together with scaled hydrogenic rates[2] for the continuum and bound processes (listed in Table I) to follow the time history of the projectile charge state. Since our main interest lies in the case of a high-Z projectile and a warm low-Z target, we have excluded various resonances processes that are important for near neutral ions and enhanced charge transfer from target to projectile where there is a coincidence in the energy levels involved. In our case, since we expect the target and projectile atoms to be highly ionized, such resonance effects are small.

TABLE I

ELECTRON RATES	o BOUND-BOUND EXCITATION & DE-EXCITATION
	o BOUND-FREE IONIZATION
	o RADIATIVE RECOMBINATION
	o (3-BODY RECOMBINATION)
ION RATES	o BOUND-BOUND EXCITATION & DE-EXCITATION
	o BOUND-FREE IONIZATION

Next we present arguments to show that even at $\sim$ solid density in the target, three body recombination is strongly suppressed by kinematic effects. To calculate the rate for this process, we must integrate the cross-section over the initial electron distribution function in energy and angle. In the reference frame of the projectile, these distributions are essentially delta-functions. Together with requirements of energy and momentum conservation and the form of the cross-section, this leads to a small result. To get a quantitative estimate, we proceed as follows. From detailed balance, we can relate the recombination differential cross-section to that for ionization. Using a Born approximation for the ionization differential cross-section, and performing the phase space integral, we finally obtain an analytic expression for the three-body rate. There are two parts to this: an angular part shown in Fig. 1 and an energy factor listed in scaled form in Table II. Even at threshold ($E/I \sim 1$, appropriate at equilibrium; where E is the equivalent electron energy, and I is the ionization energy of the least bound electron), the combination of angular and energy factors yields a suppression of 1000-10,000 of three body relative to radiative recombination for fast ions of high charge.

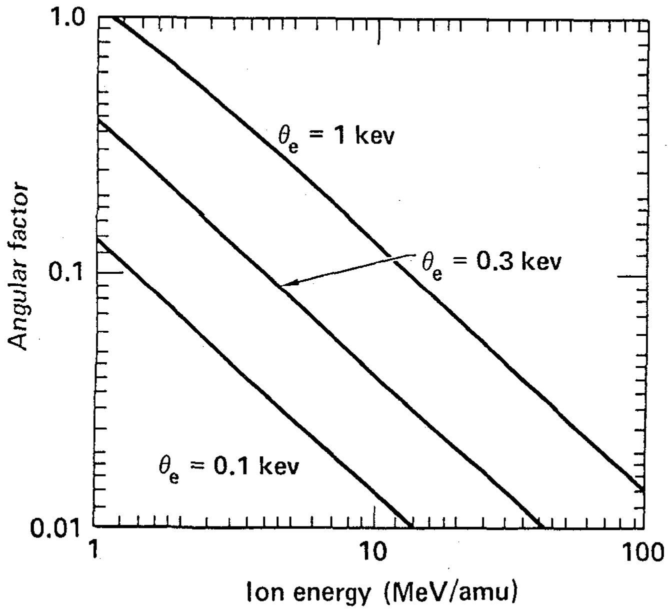


Figure 1. Plot of the dependence of three-body recombination rate on the angular point of the phase space as a function of projectile ion energy for a free electron temperature of 100 eV, 300 eV, and 1 keV.

Finally, we remark that we include the ion-ion processes by z-scaling from the electron results. As shown in Fig. 2, this is a good approximation for fast ions on fully stripped targets which is the case of greatest interest here.

TABLE II

COMPARISON OF THE THREE-BODY RECOMBINATION RATE TO THE RADIATIVE RECOMBINATION RATE

$$\frac{\text{THREE - BODY RECOMBINATION RATE}}{\text{RADIATIVE RECOMBINATION RATE}} = \text{Ro} \quad E/I \quad \frac{Ne}{No} \quad \frac{N}{Z^*}^{4}$$

$No = 1 \times 10^{23}$ $N = 1$ $Z^* = 1$

E/I	Ro
1.0	2.8×10^{-1}
5.0	4.74×10^{-3}
10.0	3.18×10^{-4}
15.0	1.02×10^{-4}
20.0	2.90×10^{-5}
30.0	6.52×10^{-6}

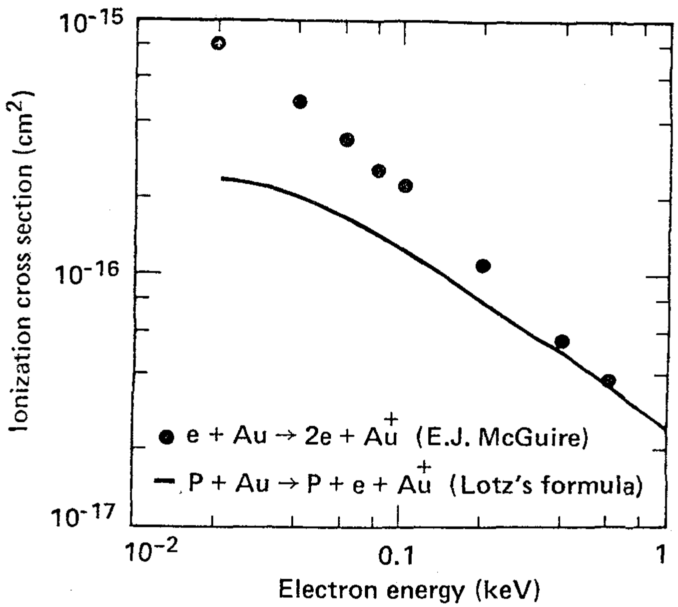


Figure 2. A comparison of total ionization cross-sections for incident electrons and protons as a function of electron energy (or $(E_p/M_p) \times Me$ for protons).

In summary, the important processes are collisional ionization balanced at equilibrium by radiative recombination. Although this sounds similar to coronal equilibrium, in the present case the narrow electron energy distribution means that the same electrons excite as recombine, whereas with Maxwellian electrons, it is the high energy ones that do the excitation and the low energy ones that recombine.

The result of solving the rate equations for various projectile ions with an energy of 46 MeV/Amu (corresponding to 9 Gev for a gold ion) is shown in Fig. 3a for electron-ion excitation and in Fig. 3b for ion-ion excitation for a target ion with a Z* of 10. For such fast ions, the equilibrium charge state is very close to fully stripped in all cases, although the time to reach equilibrium increases with projectile Z. Furthermore, although the equilibrium time decreases for the ion-ion case (Fig. 3b), the equilibrium charge is almost identical to the electron-ion case, in agreement with the Bohr criterion. Also note that the time to strip the first electrons is very short, and hence decreasing the initial stripping time is not important. To express the time equilibration time in more physical units, we list in Table III the equilibration distance (for a constant velocity ion) in units of the cold range for the ions in Fig. 3. The delay distance increases rapidly with projectile Z, and for gold ions is 1/6 of the total range, a substantial effect.

TABLE III

EQUILIBRATION DISTANCE (IN UNITS OF COLD RANGE)

Au	$\sim$	0.16
Ag	$\sim$	0.1
Cu	$\sim$	0.025
Ca	$\sim$	0.01
Si	$\sim$	0.005

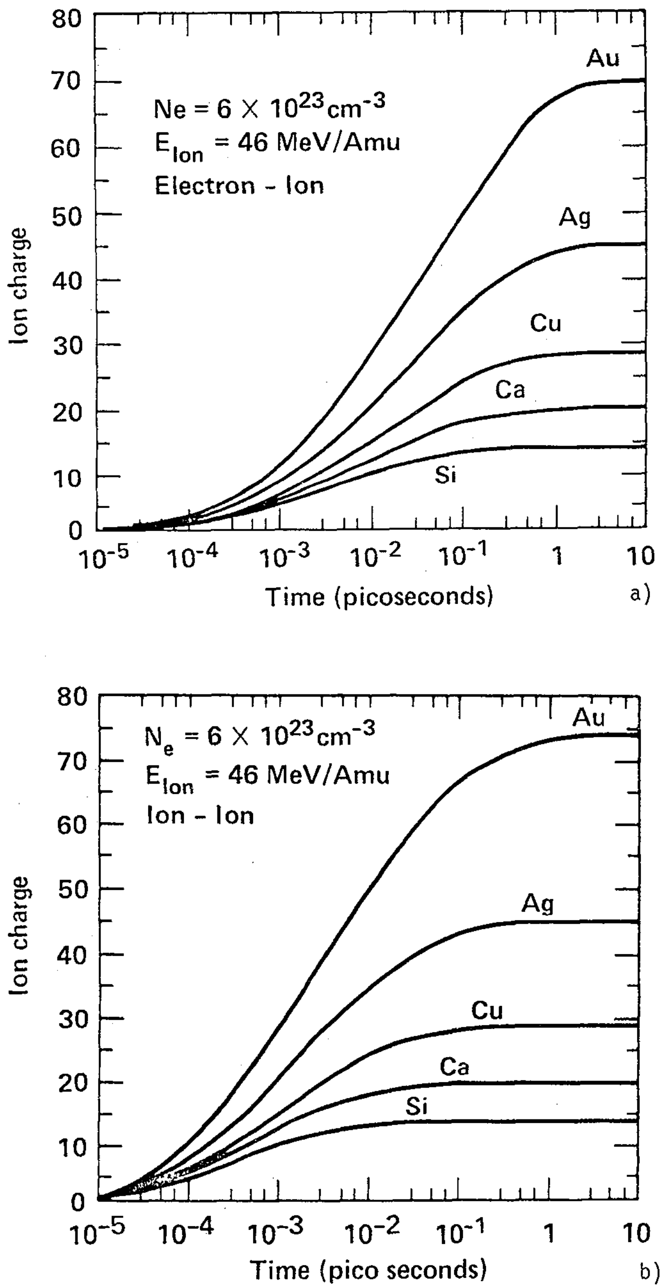


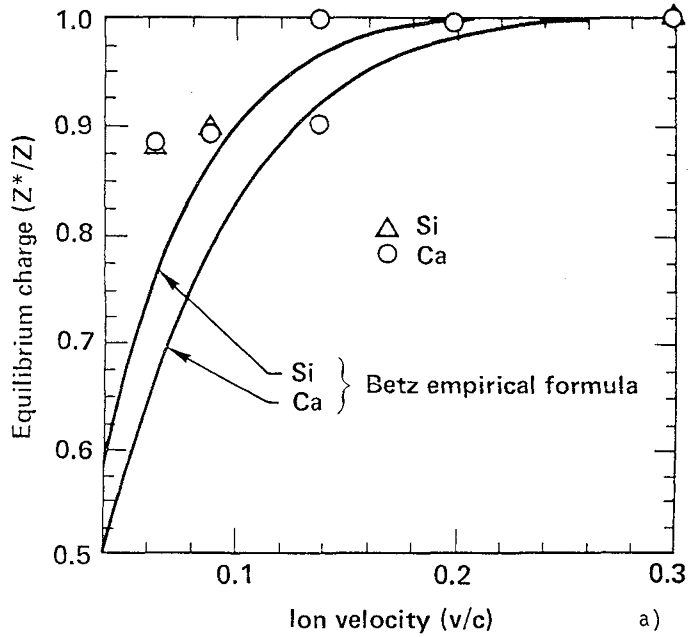
Figure 3. a,b Time dependent charge state for several ions for electron collisions (Fig. 3a) and ion collisions (Fig. 3b) for a target corresponding to fully stripped aluminum at solid density.

The calculations reported here refer a free electron density $\sim 6 \times 10$ cm^{-3}, corresponding to fully ionized aluminum at near solid density. The stripping rate is proportional to the electron density and the energy-loss rate is approximately linear in the electron density.

Therefore, we believe these results are also valid for high-Z targets. Note that the omitted effects (charge transfer, etc.) increase recombination, and hence lengthen the equilibrium distance. The main effect that would shorten the stripping distance is the ion-ion collisions; hence as the target warms up, the effect will decrease.

By repeating the calculations of Fig. 3 for lower energy ions, we can obtain the equilibrium charge for each ion as a function of projectile velocity. These results are shown in Fig. 4a and 4b for the same ions used in Fig. 3. We also show for comparison the semi-empirical Betz formula.[3] At high velocities, the agreement is very good; at medium velocities shell effects cause our results to deviate from Betz, and at low velocities (where the Betz formula starts to fail) our results are systematically high.

Finally, we mention a useful result that we obtain as a by-product of solving the rate equations, namely the radiation emission of the projectile ion as it traverses the target. We show in Fig. 5 the time integrated emission spectrum of a constant velocity 46 MeV/Amu gold ion penetrating somewhat more than a cold target range depth. Since the total radiation emission is $\sim$ 2% of the original ion energy, it is a potential source of preheat in the rest of the target.



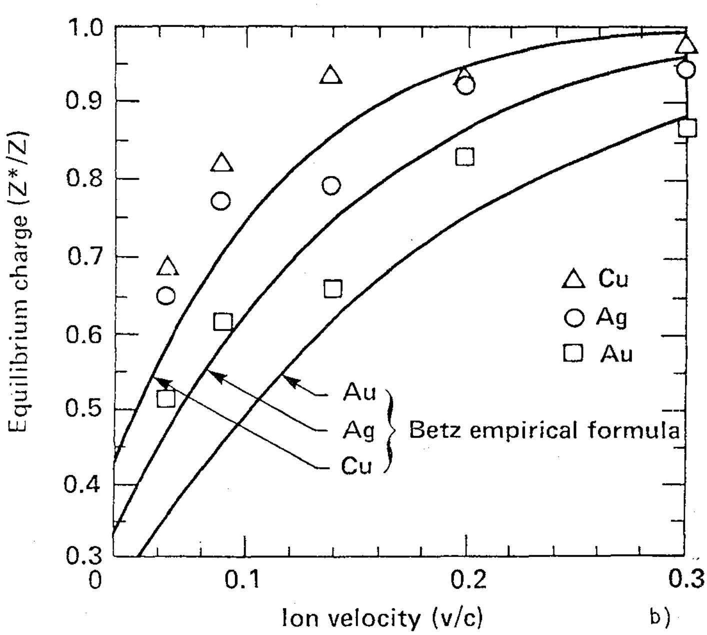


Figure 4. a,b Equilibrium charge state as a function of ion velocity for the low Z (Fig. 4a) and high Z (Fig. 4b) ions of Fig. 3.

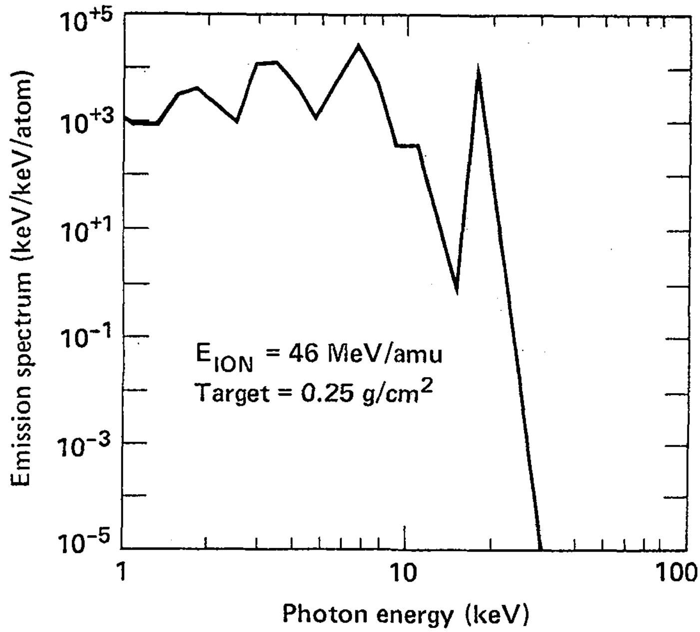


Figure 5. Time integrated emission spectrum for a gold ion traversing 0.25 g/cm^2 of cold Al.

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