44, 164 (1980); R. W. Cline, T. J. Greytak, and D. Kleppner, Phys. Rev. Lett. 47, 1195 (1981).

[3]M. Goldhaber, Proc. Cambridge Philos. Soc. 30, 561 (1934).

[4]J. P. Conner, T. W. Bonner, and J. R. Smith, Phys. Rev. Lett. 88, 468 (1952).

[5]W. Haeberli, in *Nuclear Spectroscopy and Reactions*, edited by J. Cerny (Academic, New York, 1974), Pt. A, p. 185.

[6]B. P. Ad'yasevich and D. E. Fomenko, Yad. Fiz. 9, 283 (1969) [Sov. J. Nucl. Phys. 9, 167 (1969)].

[7]G. Hale and D. Dodder, in *Few Body Systems and Nuclear Forces II*, Lecture Notes in Physics Vol. 87, edited by H. Zingl, M. Haftel, and H. Zankel (Springer-Verlag, New York, 1978), p. 523, and private communication.

[8]L. Wolfenstein, Phys. Rev. 75, 1664 (1949).

[9]J. A. Pople, W. G. Schneider, and H. J. Bernstein, in *High-Resolution Nuclear Magnetic Resonance* (McGraw-Hill, New York, 1959), Appendix B.

[10]H. Kopfermann, in *Nuclear Moments*, Pure and Applied Physics Vol. 2, edited by H. S. W. Massey (Academic, New York, 1958), Chap. 1.

[11]D. L. Jassby, Nucl. Fusion 17, 309 (1977).

[12]W. B. Kunkel, in *Fusion*, edited by E. Teller (Academic, New York, 1981), Vol. I, Pt. B, Chap. 12.

Charge State and Slowing of Fast Ions in a Plasma

E. Nardi[(a)] and Z. Zinamon
Weizmann Institute of Science, Rehovot 76100, Israel
(Received 10 June 1982)

The charge state of a projectile ion traveling through a plasma target under conditions relevant to ion-beam fusion is calculated. It is found that, at the projectile energies and target parameters considered, the projectile ionization is significantly higher than that of the same projectile species in a cold target. The resulting strong effects on the range and on the shape of the energy deposition profile are shown in several examples of full dynamic calculations.

PACS numbers: 52.40.Mj, 29.70.Gn, 61.80.Mk

The processes involved in the slowing of fast ions in high-temperature plasmas are of prime interest in the study of inertial-confinement fusion systems using intense ion beams.[1] The case of proton beams was studied by Mosher[2] and Nardi, Peleg, and Zinamon.[3] In particular, the latter authors applied the theory of the plasma dielectric function to calculate the contribution of the free electrons to the stopping power, and constructed a model of the ions in order to extend Bethe's theory to treat the stopping power due to electrons bound in the plasma ions. Only proton slowing was considered in Ref. 3, because with heavier ions the charge state of the projectile has to be known. The problem of the charge state of projectiles moving in cold matter has been studied over a long period of time.[4,5] In that case the charge state of the projectile is determined by the competition between electron loss by collisions and capture from bound states in the target atoms. As was pointed out by Bell,[5] it is much more difficult for the projectile to capture a free electron than a bound electron. The reason is that for a free-electron capture to take place the excess binding energy has to be gotten rid of by one of the following processes: (a) radiative recombination, (b) three-body recombination, or (c) dielectronic recombination. Also, loss processes by collisions with the highly stripped plasma ions could be more efficient than those due to collisions with cold target atoms. It is to be expected, therefore, that the charge state of a projectile moving in a plasma will be quite different from that in a cold target. The effect is expected to become less important at high projectile energies, when capture from bound states is also hindered by the large relative kinetic energy. Work on this subject was first reported by Bailey, Lee, and More.[6] An estimate was made by Mehlhorn[7] without specifically considering recombination processes. In this work we present a simplified model for the calculation of charge state of ions moving in various ionized targets.

Electron loss due to collisions of the projectile with the background ions is calculated by the binary encounter approximation (BEA).[8] This approximate model agrees with the semiclassical description,[8] and with the plane-wave Born approximation.[9] For accurate agreement with experiment the Coulomb deflection effect and the binding-energy effect[9] should be included in the Born approximation. However, we did not find it necessary to include these corrections; the calculations, which are required for ions of a wide range of charge states, are thus greatly simplified, and the main results will be shown to be insensitive to large variations in cross sections. The total cross section for ionization of the projectile by the plasma ions is calculated from[8]

$$\sigma_{Ii} = \sum_n N_n \sigma_n = \sum_n (N_n Z_{1n}{}^2 \pi e^4 / U_n{}^2) G(V_n). \quad (1)$$

Here N_n is the number of electrons in the shell n, U_n is the binding energy of the ionized electron, V_n is the scaled velocity v/v_{en} where v is the projectile velocity and v_{en} is the orbital velocity of the ionized electron, and $G(V_n)$ is calculated by McGuire and Richard[10] according to Gryzinski. Z_{1n} in Eq. (1) is the effective charge of the background ions for the collision, determined, following Bell,[5] as the charge inside a radius l, which is equal to $(\sigma_n/\pi)^{1/2}$, where σ_n is the cross section for the ionization of each electron in the BEA.

The cross section for ionization of the projectile by the plasma free electrons is calculated from[11]

$$\sigma_{Ie} = [4.5\times 10^{-14} N \ln(E_e/U)]/UE_e, \quad (2)$$

where N is the number of electrons in the projectile shell considered, U is their ionization energy, E_e is the larger of $\frac{1}{2}mv_{te}{}^2$ and $\frac{1}{2}mv^2$, and v_{te} is the thermal velocity of the plasma electron.

Capture by the projectile of bound electrons in the plasma ions is calculated with Bell's theory.[5] According to this classical theory the cross section for capture is determined by whether the kinetic energy in the rest system of the projectile of a bound electron liberated in the collision is more or less than the potential energy. We obtain the required energies and forces for each electron shell in the various ions using the Hartree-Fock-Dirac-Slater model of the atom.[12] Capture cross sections obtained by this method for Al^{+13} at 5 MeV incident on a H-atom target are in good agreement with results of three-body classical simulation studies,[13] except at low projectile velocities.

Capture by the projectile of free plasma electrons by the radiative recombination process is calculated according to Seaton[14]:

$$\alpha_{ZR} = 1.3\times 10^{-9}(Z+1)^2 I_Z{}^{1/2} T_e{}^{-1} n_e, \quad (3)$$

where α_{ZR} is the radiative recombination rate in cubic centimeters per second for an ion into a hydrogenlike charge state Z, I_Z is the ionization energy for this ion, T_e is the electron temperature in kelvins, and n_e is the free-electron density. Equation (3) is a valid approximation in cases where v is less than v_{te}. At higher projectile velocities T_e can be replaced by $\frac{1}{2}mv^2/k$ where m is the electron mass and k is the Boltzmann constant.

Capture of free electrons by the dielectronic recombination process[15] is treated by taking the value of $\alpha_D = 10^{-11}$ cm^3 s^{-1}. This is believed to be an upper-limit estimate, since it is the largest value quoted,[16] neglecting the effect of collisions at the high densities considered here, which are expected to considerably reduce the net recombination rate.[17]

Free-electron capture by the three-body recombination process is calculated with the adaptation by Zel'dovich and Raizer[18] of Thomson's classical theory.[19] In the case $v < v_{te}$ this yields for the recombination coefficient

$$\alpha_T = v_{te} \pi^2 R_0{}^5 Z^{-2} n_e, \quad (4)$$

where $R_0 = Ze^2/\frac{3}{2}kT$ is the effective radius of the Coulomb interaction between an electron and an ion of charge Z. In the case $v > v_{te}$, v_{te} is replaced by v in Eq. (4) and $\frac{3}{2}kT$ is replaced by $\frac{1}{2}mv^2$ in R_0. The validity of the classical model ($2Ze^2/mv^2 > h/mv$) was checked for the range of parameters where free-electron capture is important.

The cross sections in Eqs. (1) and (2) are converted to rate coefficients α_{Ii}, α_{Ie}. The distribution of charge states among the projectiles traversing the target is now calculated dynamically by solving the set of coupled equations

$$dP_j/dt = -P_j(\alpha_R{}^j + \alpha_I{}^j) + P_{j+1}\alpha_R{}^{j+1} + P_{j-1}\alpha_I{}^{j-1}. \quad (5)$$

Here P_j is the fraction of projectiles in charge state j; $\alpha_R{}^j$ and $\alpha_I{}^j$, are, respectively, the total rate coefficients of recombination and ionization for charge state j, which are the instantaneous values determined by the charge state, the projectile velocity, and the plasma parameters. The average charge state, using j^2 weights, is used in the energy-loss calculation. We use our model[3] to determine the contribution of the target bound electrons to the stopping power and a simplified treatment,[20] rather than the full dielectric function calculation,[3] for the contribution of the plasma free electrons. In each calculation step the new values of the energy and velocity are used to advance the projectile and a new step

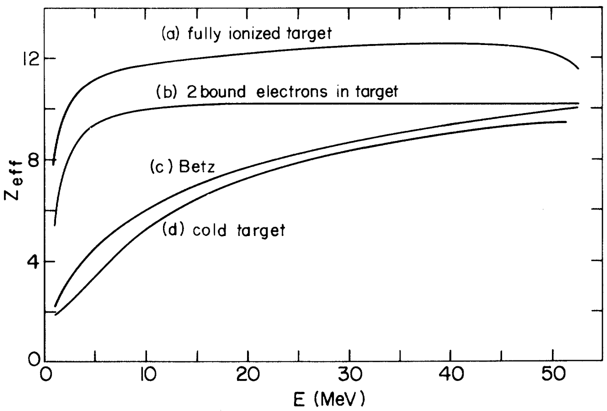

FIG. 1. The charge state Z_{eff} of an aluminum ion with initial energy of 54 MeV as a function of its energy as it is slowed in carbon targets at various temperatures. The transition from $Z=3$ is very fast and not shown. The empirical curve of Betz (Ref. 21) is shown for comparison.

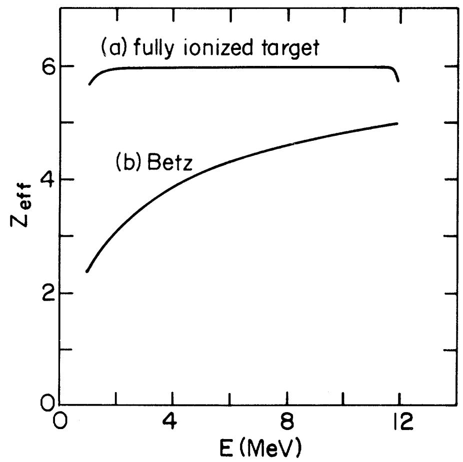

FIG. 2. The charge state Z_{eff} of a carbon ion with initial energy of 12 MeV as a function of its energy as it is slowed in a fully ionized lithium target as compared with the empirical curve of Betz (Ref. 21) for a cold target.

is started.

We report the results of calculations of the slowing of carbon and aluminum projectiles in lithium and carbon targets. The carbon targets were at a density of 10^{-2} g/cm^3 and temperatures of 25 eV (two bound electrons) and 100 eV (no bound electrons). The projectiles were aluminum ions at initial energy of 54 MeV and initial charge state of $Z=3$. The calculated charge state versus energy of the projectile as it is slowed down in the target are shown in Fig. 1. For comparison we show the empirical values of the equilibrium charge state given by Betz[21] for cold targets. The very significant difference is immediately noted. The role of the more efficient capture from bound states is seen from the relative positions of the curves for zero, partial, and full ionization in the target. The same calculation was also carried out for a cold target in order to test Bell's theory and the result is also shown in Fig. 1. In order to reach this degree of agreement between theory and experiment the value of l in Bell's model had to be adjusted to $l'=0.5l$, which is reasonable in view of its qualitative nature. The same adjustment was used in calculating curve b of Fig. 1. In Fig. 2 we show results for the interaction of 12-MeV carbon ions with a lithium target at a temperature of 25 eV (fully ionized) as compared with Betz's curve.[21] Again, the pronounced difference between plasma and cold targets is evident. Our results disagree with the charge states in plasma proposed by Mehlhorn.[7]

These results were checked to be rather insensitive to large variations in the cross sections for capture from free states: Multiplying all these cross sections by a factor of 10 would shift curve a in Fig. 1 by less than one charge state.

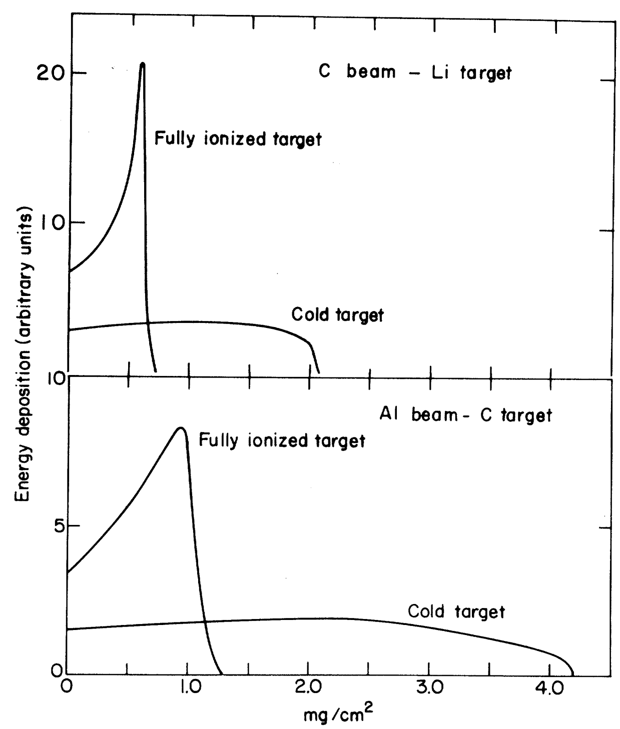

FIG. 3. Energy deposition profiles. Top, 12-MeV carbon beam in a fully ionized and in a cold lithium target. Bottom, 54-MeV aluminum beam in a fully ionized and in a cold carbon target.

Energy deposition profiles are shown in Fig. 3. For comparison deposition profiles are shown which are based on cold-matter stopping power and Betz's cold-matter charge for C projectiles, and our cold charge-state calculation for Al projectiles. Our cold stopping ranges are in good agreement with Littmark and Ziegler[22] for C and are slightly larger than theirs for Al projectiles. It is evident that the combined effect of the correct stopping power and charge state is range shortening by a factor of about 3, of which the charge-state correction contributes about a half. We note the difference in shape between the two deposition curves: In the cold target the drop in projectile ionization causes the Bragg peak to be washed out, in contrast to the plasma target, in which the high projectile ionization is maintained.

In conclusion, the charge state of projectile ions in plasma targets can be different from its value in cold targets which results in considerable effects on the energy-deposition profile. The reason is that with free electrons, higher projectile ionization is required in order for the recombination processes to compete with the ionization processes. In the case of carbon projectiles in lithium targets the effects should occur at a temperature of about 25 eV. Such temperatures are obtainable in present-day technology, and verifying experiments can be done, provided sources are available of sufficiently intense carbon ion beams, or even, say, proton beams containing enough carbon ions.

---

[a]Also at Soreq Nuclear Research Center, Yavneh, Israel.

[1]G. W. Kuswa, J. P. Quintenz, B. D. Seidel, D. J. Johnson, C. W. Mendel, Jr., E. J. T. Burns, D. Fehl, R. J. Leeper, F. C. Perry, P. A. Miller, M. M. Widner, and A. V. Farnsworth, Jr., in Proceedings of the Fourth International Topical Conference on High Power Electron and Ion Beam Research and Techniques, Palaiseau, France, June 1981, edited by H. J. Doucet and J. M. Buzzi (unpublished), Vol. I, p. 3, Sandia Laboratory Report No. 81-672C; D. Mosher, D. G. Colombant, S. A. Goldstein, and P. F. Ottinger, *ibid.*, Vol. I, p. 19.

[2]D. Mosher, in Lawrence Berkeley Laboratory Report No. LBL-5543, edited by R. O. Bangerter, W. B. Herrmannsfeldt, D. L. Judd, and J. Smith, 1976 (unpublished), p. 39.

[3]E. Nardi, E. Peleg, and Z. Zinamon, Phys. Fluids 21, 574 (1978).

[4]N. Bohr, K. Danske Vid. Selsk. Mat.-Fys. Medd. 18, 18 (1948); H. D. Betz, Nucl. Instrum. Methods 132, 19 (1976); S. Kreussler, C. Varelas, and W. Brandt, Phys. Rev. B 23, 82 (1981).

[5]G. I. Bell, Phys. Rev. 90, 548 (1953).

[6]D. S. Bailey, Y. T. Lee, and R. M. More, Bull. Am. Phys. Soc. 26, 900 (1981).

[7]T. A. Mehlhorn, J. Appl. Phys. 52, 6522 (1981).

[8]P. Richard, in *Atomic Inner Shell Processes I*, edited by B. Crasemann (Academic, New York, 1975), p. 73.

[9]W. Basbas, R. Brandt, and R. Laubert, Phys. Rev. A 7, 983 (1973).

[10]J. H. McGuire and P. Richard, Phys. Rev. A 3, 1374 (1973).

[11]W. Lotz, Z. Phys. 206, 203 (1967), and 216, 241 (1968).

[12]D. Liberman, J. Waber, and D. T. Cromer, Phys. Rev. 137, A27 (1965).

[13]R. E. Olson and A. Salop, Phys. Rev. A 16, 531 (1977).

[14]M. J. Seaton, Mon. Not. Roy. Astron. Soc. 119, 81 (1959).

[15]A. Burgess, Astrophys. J. 139, 776 (1964).

[16]Y. Hahn, Phys. Rev. A 22, 2896 (1980).

[17]I. L. Beigman, L. A. Vainshtein, and B. N. Chichov, Zh. Eksp. Teor. Fiz. 80, 964 (1981) [Sov. Phys. JETP 53, 490 (1981)]; T. P. Donaldson, Culham Laboratory Report No. CLM-R 53, 1976 (unpublished).

[18]Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Academic, New York, 1966), Vol. I, p. 406.

[19]H. S. W. Massey and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena* (Oxford Univ. Press, London, 1952).

[20]G. Bekefi, in *Plasma Physics*, Proceedings of the Les Houches Summer School of Theoretical Physics, edited by C. de Witt and J. Peyraud (Gordon and Breach, New York, 1972), p. 1.

[21]H. D. Betz, Rev. Mod. Phys. 44, 465 (1972).

[22]U. L. Littmark and J. F. Ziegler, *Range Distribution for Energetic Ions in All Elements* (Pergamon, New York, 1980).