Electron Loss Process and Cross Section of Multiply Charged Ions by Neutral Atoms

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§1. Introduction

Recently the significance of experimental and theoretical results on the electron loss and capture of ions in matter has become to play an impotant role in the charge equilibrium problems of fusion plasma physics and of accelerator physics. In spite of these impotance, only a few works have been made in experiments as well as in theoretical calculations[1,2] for electron loss processes.

In the present report, we calculate electron stripping cross section by using the binary encounter approximation (BEA). The electron loss process of multiply charged ion A^{q+} (atomic number Z_1) by the collision with a neutral atom B (atomic number Z_2) is expressed as

$$A^{q+} \quad + \quad B \longrightarrow A^{(q+1)+} \quad + \quad e \quad + \quad B(\Sigma\ ). \qquad (1)$$

After an electron is stripped from the ions, charge of ions becomes (q+1) and B does neutral or ionized states i.e., B(Σ) means all electronic states of the atom including ionized states. Our treatment of the electron loss processes is based on BEA , in which the nucleus of B screened by the surrounding electrons collides with electrons in the ion A^{q+}. The basic approximation in BEA is that the ion interacts with only one electron or neucleus of the target atom at a time. One of the difficulty seems to come from the fact that the binding energy of an outermost electron in A^{q+} is usually much larger than that in the B atom. The electron stripping cross section for the process(1) is expressed to be smaller than that of ionization or excitation of the B atom.

In the calculation for Li^{2+} + H, we have found that BEA will give approximately reliable results of the process(1)[2,3].

The characteristic feature of this process lies in the large magnitude of momentum transfered to the electrons in the ion A^{q+} on occasions of close collisions with the neutral atom B. Such collision with large momentum transfer can well be approximated by the classical description. This feature also supports that BEA is considered to be one of the proper method.

§ . Formulation and Calculation

The evaluation of cross sections requires information about the momentum distribution of electrons in the ion. In the present paper, the momentun distribution f(p)dp and the probability $I_r(p)dp$ of an electron having momentum between p and p+dp at r in a potential V(r) are obtained by the Thomas-Fermi (TF) statistical model[4]:

$$f(p)\,dp = \int_0^{r(p)} I_r(p)dp\, n(r)\, 4\pi r^2\, dr = 4\pi \int_0^{E(p)} I_r(p)dp\, n(r)\, r^2 \left(\frac{dr}{dE}\right) \times dE \qquad (2)$$

and

$$I_r(p)dp = \begin{cases} \dfrac{4\pi p^2 dp}{4\pi p_{max}^3/3} = \dfrac{3p^2}{p_{max}^3}dp & \text{for } p \leq p_{max} \\ & \text{for } p > p_{max} \end{cases} \qquad (3)$$

where in Eqn.(2), r is considered as a function of E as r(E) with the relation $(p^2/2m) + V(r) = E$ and $n(r) = (8\pi/3h^3)\,p_{max}^3(r)$ is the number of electron per unit volume at the distance r from nucleus. The value of the maximum momentum p_{max} is given through the TF equation:

$$\frac{d^2\phi}{dx^2} = x^{-\frac{1}{2}}\,\phi^{\frac{3}{2}}$$

with the boundary condition

$$\phi(0) = 1, \quad \phi(x_0) = 0, \text{ and } -x_0\left(\frac{d\phi(x)}{dx}\right)_{x=x_0} = \frac{Z-N}{Z}$$

$$r = \lambda Z^{-\frac{1}{3}} a_0 x, \quad \lambda = \frac{1}{2}\left(\frac{3\pi}{4}\right)^{\frac{2}{3}}$$

$$P_{max}(x) = \left(\frac{2me^2Z}{r}\right)^{\frac{1}{2}} \left(\frac{\phi(x)}{x}\right)^{\frac{1}{2}},$$

$$\nabla^2 V(r) = -4\pi n(r) e^2, \tag{4}$$

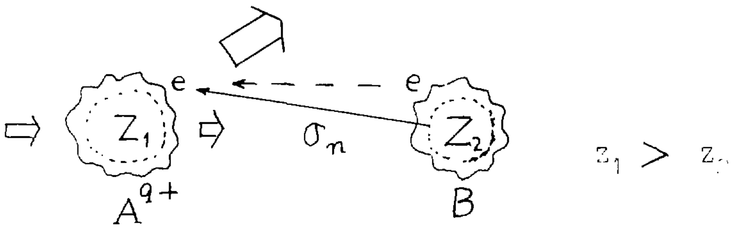
$$n(r) = (8\pi/3h^3)(2m(V(r)-E_0))^{\frac{3}{2}}, \quad P_{max}^2 = V(r) - E_0 \tag{5}$$

with $V(r)=Z_1 e^2/r$ for $r \rightarrow 0$,
where E_0 is obtained such that $4\pi\int n(r) r^2 dr = N$, and N is the number of electrons in the ion.

When we define the ionization cross section $\sigma_n^{(i)}(v,w)$ in the laborarory frame for the collision between a nucleus with a velocity v and the atomic electron with a velocity w[5,6], the cross section for electron stripping from A^{q+} by the collision with the target nucleus $\sigma_n(v)$ is given as

$$\sigma_n(v) = \int_0^\infty \sigma_n^{(i)}(v, w) f(w) dw, \tag{6}$$

where f(w) is a velocity distribution in Eqn.(2) which is determined by the TF model.



Schematic of collision in electron stripping.

§3. Results and Discussion

Confine ourselves to the case where the screening effect of B nucleus by electrons is negligible i.e., $Z_2 \ll q$. For the time being we treat $Z_1 = 1,2$ and $q \geq 3Z_2$. Under these background and Eqs.(2)-(6) we have made calculations of process (1) using BEA in the case of C^{q+}, Ne^{q+}, and Ar^{q+} projectile ions ($q=3 \sim Z$) and H target atom. Figures(1),(2), and (3) shows the preliminary results for electron stripping cross sections.

As the next step, we consider to treat Eq.(2) by the another transformation; we examine the deflection from Coulomb potential. The momentum distribution $f(p,E)dpdE$ in a μ-space of an electron having momentum between p and p+dp and binding energy between E and E+dE is given by

$$f(p,E)\, dp\, dE = \frac{8\pi}{h^3} r^2(E,p) \left| \frac{dr}{dv}(p,E) \right| dE\, dp, \tag{7}$$

where V denotes a potential energy.
The distribution function is defined in the same condition Eq.(2) as for Eq.(7). For the TF method it is convenient to introduce new quantities $\tilde{V}$ as

$$\tilde{V} = \frac{\phi(x)}{x} \tag{8}$$

and then

$$V = -\frac{Z^{\frac{4}{3}} e^2}{\lambda a_0} \tilde{V}. \tag{9}$$

From these Eqs. it follows that

$$f(p, \varepsilon) = \left(\frac{a_0}{h}\right)^3 8\pi \lambda^4 Z^{-\frac{7}{3}} F(\tilde{V}) \tag{10}$$

with $= (a_0/e^2) E$ and

$$F(\tilde{V}) = x \left| \frac{dx}{d\tilde{V}} \right| = \frac{1}{\tilde{V}^4} \frac{f^3(\tilde{V})}{1 - \frac{\phi'(\tilde{V})}{\tilde{V}}} \tag{11}$$

$$f(\hat{V}) = \phi(x(\tilde{V})), \qquad \check{V} = \lambda Z^{-\frac{4}{3}}(\varepsilon + a_0 p^2/2\hbar^3)$$

In Eq.(11), the relation $f^3(V)/\left[1 - \phi'(\hat{V})/\hat{V}\right]$ represents the deflection from the Coulomb potential. The asymptotic form has the following behavior:

$$F(V) \longrightarrow \frac{1}{\tilde{V}^4} \qquad \text{for } \tilde{V} \longrightarrow \infty .$$

Figure(4) shows the calculation results ($q=1 \sim Z$) using this method. Similarly, the calculations of cross sections for electron stripping from A^{q+} by the collision with electrons in the target atom , $\sigma_e(v)$, is now in progress. The effects of

$\sigma_e(v)$ on the total electron stripping cross section will be revealed by the effective interaction between electrons of the projectile ion and the target atom.

References

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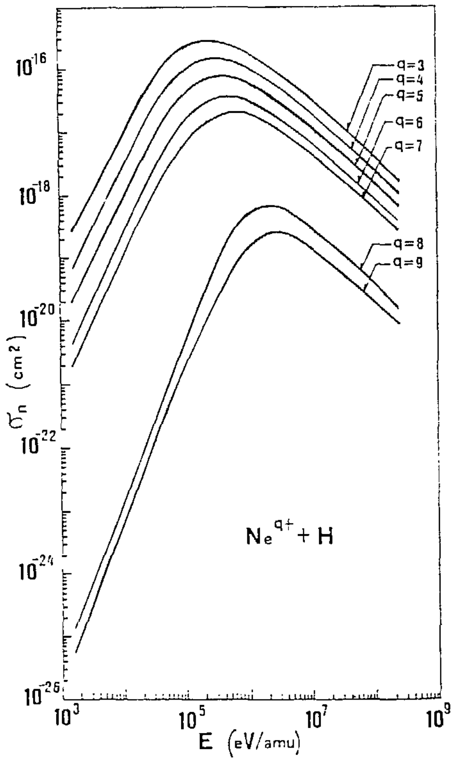
Figure Captions

Fig.1. Electron stripping cross sections for C^{q+} -ion by collision with H-atom.

Fig.2. Electron stripping cross sections for Ne^{q+} -ion by collision with H-atom.

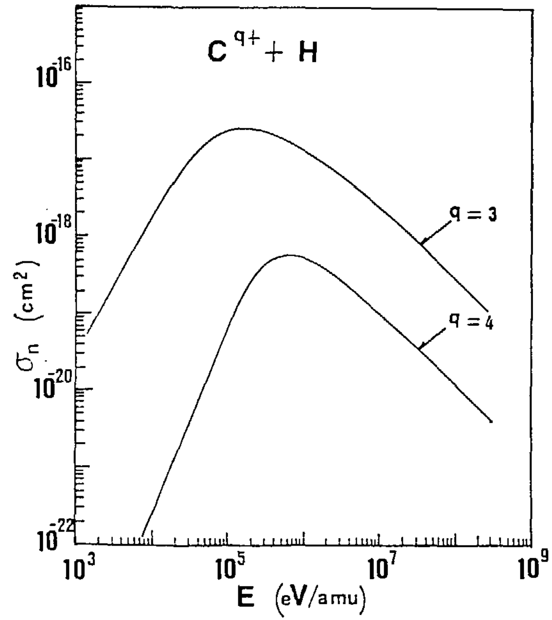
Fig.3. Electron stripping cross sections for Ar^{q+} -ion by collision with H-atom.

Fig.4. Electron stripping cross sections for Ne^{q+} -ion by collision with H-atom by using the method Eq.(11). Projectile ion has the charges $q = 0 \sim 5$.



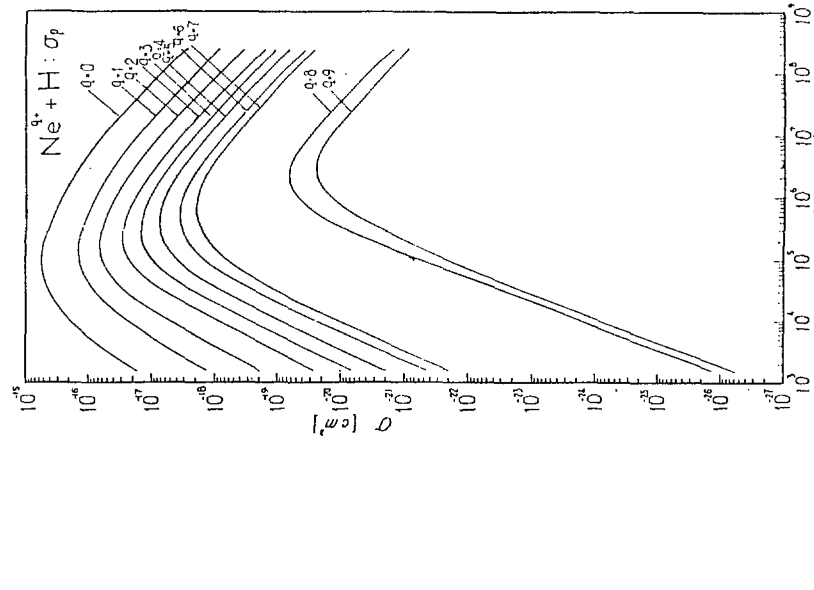
q=3
q=4
q=5
q=6
q=7
q=8
q=9
Ne q+ + H
σn (cm2)
E (eV/amu)
10-16
10-18
10-20
10-22
10-24
10-26
10 3
10 5
10 7
10 9

Fig.2



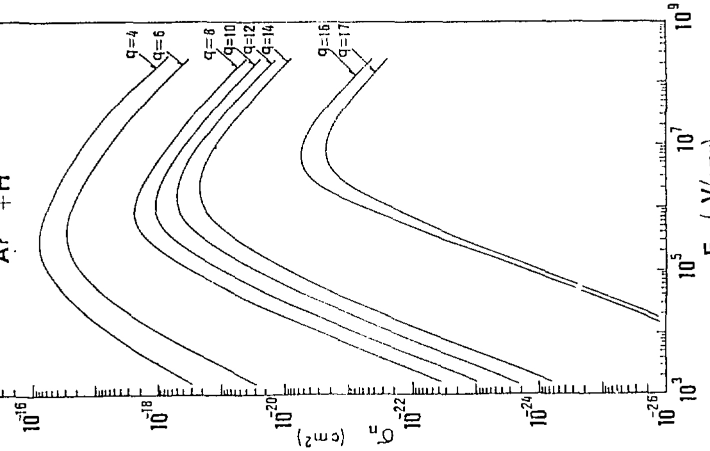
C q+ + H
q = 3
q = 4
σn (cm2)
E (eV/amu)
10-16
10-18
10-20
10-22
10 3
10 5
10 7
10 9

Fig.1



$Ne^{q+} + H : \sigma_p$
q=0
q=1
q=2
q=3
q=4
q=5
q=6
q=7
q=8
q=9
σ [cm²]
E [eV/amu]

Fig.4



$A_r^{q+} + H$
q=4
q=6
q=8
q=10
q=12
q=14
q=16
q=17
σn (cm²)
E (eV/amu)

Fig.3