Electron Emission in Ion-Alkali Atoms Collision Process: Three Body Effect

Salman Hamza Hussein¹, T A Selman² and S I Easa³

¹Veterinary Medicine College, Qadissyah University.
²Physics Department, Science College, Basrah University.
³Physics Department, Education College, Basrah University.
Email: salmanhamza@qu.edu.iq

Abstract. Double differential scattering cross section for emitted electron from ground and excited states when the Ar⁺⁺ (75, 85 and 95 MeV/u) scattered off Alkali atom have been calculated within Born approximation following Stolterfoht et al, theoretical model. The emitted electrons from the excited state give large differential cross section comparison with the ground state. Many features of the scattering process are also discussed.

Key word: Ion-Atom Collision, Differential Cross Section, Three Bodies Effect.

1. Introduction

Spectroscopic tool for studying plasma physics, scattering processes and radiation physics is the electron emission following momentum transfer during the collision process of fast ion with atoms [1-5].

Differential cross section (DCS) for electron emission is the main application and basic quantity which is calculated in theoretical treatments of inelastic scattering of the charged particles with atoms or molecules [6-9].

Theoretical treatment of inelastic collision processes of charged particles with atoms or molecules can be classified into two types; those dealing with fast collision processes and others with slow one. The velocity of the incident particles used in the classification is that the particle velocity is fast or slow with respect to a mean orbital velocity of atomic electrons in the shell or subshell [10,11].

When charged particles are incident, significant momenta can be transfer in collision to the atomic electrons as virtual photon and this momenta or energy change the internal states of atoms or molecules [12].

Electron emission spectra are exhibiting various characteristic features which can be associated with particular ionization process. Electrons emitted with low energies particularly important because these electrons have the large probability for emitting from atoms or molecules. These low-energy electrons referred to the soft-collisions and produced mainly in large impact-parameter collisions. When the velocity of the projectile is much larger than the velocity of the active
bound electron, the momentum transfer in a soft collision is very small on an atomic scale. On the other hand, an ejected electron may carry away a significant amount of momentum, when the final electron momentum is larger than the momentum transfer, a third body is required balance to missing momentum, hence, if no other particle ids ejected in the collision, the target nucleus has to take part in the ionization process. Therefore, soft collisions at high projectile energy cab attributed to three-body effect collision involving the projectile, the active electron and the residual target ion[7,13]. Figure (1) illustrated the diagram of three body effect

Figure (1) illustrated the diagram of three body effect[8].

2. Theory

In the framework of Born approximation, the double-differential cross section (DDCS) emission of electrons with energy $\epsilon$ into the solid angle $\Omega$ is given by [8, 11]:

$$\frac{d\sigma}{d\epsilon d\Omega} = 4Z_p^2 M^2 \frac{k_e}{k_i} k \int_{k_{\text{min}}}^{k_{\text{max}}} \frac{|F_{if}(K)|^2}{K^4} d\Omega_f \quad (1)$$

Where $k$ electron is ejected momentum, $Z_p$ and $M$ are the projectile charge and reduced mass, respectively. $F_{if}(K)$ is the atomic form factor and $\Omega_f$ is the solid angle of the scattering ion: and it is given by

$$d\Omega_f = \sin\theta_f d\theta_f d\phi_f \quad (1 - a)$$

And $\vec{k}$ represents the momentum transfer ($\vec{k} = \vec{k}_f - \vec{k}_i$) and its value is

$$k = \left( k_i^2 + k_f^2 - 2k_i k_f \cos\theta_f \right)^{1/2} \quad (1 - b)$$

Where $\theta_f$ is the scattering angle of ion.
The minimum momentum transfer $K_{min}$ and the maximum momentum transfer $K_{max}$ associated with ion velocity as

$$K_{min} \equiv \frac{\Delta E}{V_p} \quad (1 - c)$$

$$K_{max} = 2V_p \quad (1 - d)$$

Where $\Delta E$ is the energy transfer.

The atomic form factor is given by \(^8\),

$$F_{if}(K) = \int \phi_f^*(r)e^{-ikr}\phi_i(r)\,dr \quad (2)$$

Where $\phi_i$ and $\phi_f$ are the initial and final state of the active electron, respectively.

It is useful to write the atomic factor in the following expression \(^7\),

$$F_{if}(K) = \sum_{lm} F_{lm}(K)Y_{lm}(\Omega) \quad (3)$$

This expression is applied to study the individual multi-pole terms. Where $Y_{lm}(\Omega)$ are spherical harmonic for angular momentum $l$ and the magnetic quantum number $m$ of the final state. Then the form factor $F_{lm}(K)$ can be expressed as

$$F_{lm}(K) = \sqrt{4\pi} \, e^{i\delta_l}Y_{lm}(\Omega_K)f_{\ell ln}(K) \quad (4)$$

Where

$$f_{\ell ln}(K) = \int R_{\ell l}(r)j_l(Kr)R_{st l}(r)r^2\,dr \quad (5)$$

is the radial matrix elements containing a Bessel function $j_l(Kr)$ and the radial wave functions $R_{st l}(r)$ and $R_{\ell l}(r)$ associated with $\phi_i$ and $\phi_f$. $\delta_l$ is the phase shift and the solid angle $\Omega_K$ specifies the direction of the momentum transfer.

Therefore the DDCS in equation (1) becomes as;

$$\frac{d\sigma}{d\varepsilon d\Omega} = 4Z_p^2M^2\frac{k_f}{k_i}k\int_{K_{min}}^{K_{max}} \left| \sum_{lm} \frac{F_{lm}(K)}{K^2}Y_{lm}(\Omega) \right|^2 d\Omega_f \quad (6)$$

The integral over azimuthal angle $d\varphi_f$ of the solid angle $d\Omega_f = \sin\theta_f d\theta_f d\varphi_f$ gives rise to the constraint $m = \hat{m}$.

The polar angle $d\theta_f$ can be expressed in term of momentum transfer from equation (1-b) as

$$\sin\theta_f d\theta_f = (K_iK_f)^{-1}KdK \quad (7)$$
After regrouping the diagonal $l = \ell$ and non-diagonal $l \neq \ell$ terms, one can obtain

$$\frac{d\sigma}{d\varepsilon d\Omega} = 8\pi \frac{Z_p^2}{V_p^2} k \left\{ \sum_{lm} b_{\ell m} |Y_{\ell m}(\Omega)|^2 + \sum_{l \neq \ell m} c_{\ell m} Y_{\ell m}^*(\Omega) Y_{\ell m}(\Omega) \right\} \quad \cdots (8)$$

Where the coefficients

$$b_{\ell m} = \int_{K_{\min}}^{K_{\max}} \frac{|F_{\ell m}(K)|^2}{K^3} dK \quad \cdots (9 - a)$$

And

$$c_{\ell m} = \int_{K_{\min}}^{K_{\max}} \frac{F_{\ell m}^*(K) F_{\ell m}(K)}{K^3} dK \quad \cdots (9 - b)$$

Equations (9) represent the contribution of individual angular momenta and their interfaces, respectively.

By substitute dipole term $l = 1$ into equation (8) to get simple formula for DDCS as the following

$$\frac{d\sigma}{d\varepsilon d\Omega} = 8\pi \frac{Z_p^2}{V_p^2} k \left\{ b_{1-1} |V_{1-1}(\Omega)|^2 + b_{10} |V_{10}(\Omega)|^2 + b_{11} |V_{11}(\Omega)|^2 + c_{100} Y_{10}^*(\Omega) Y_{10}(\Omega) \right\} \quad \cdots (10)$$

Or

$$\frac{d\sigma}{d\varepsilon d\Omega} = A + B \sin^2 \theta + C \cos \theta \quad \cdots (11)$$

Where

$$A = 6 \frac{Z_p^2}{V_p^2} k b_{10} \quad \cdots (12 - a)$$

$$B = 3 \frac{Z_p^2}{V_p^2} k (b_{11} + b_{1-1} + b_{10}) \quad \cdots (12 - b)$$

$$C = 2\sqrt{3} \frac{Z_p^2}{V_p^2} k c_{100} \quad \cdots (12 - c)$$

Equations (11) represent the DDCS due to the three-body effect for electron emitted in ion-atom collision. The first and the second terms represent dipole term ($l = 1$) but the third term represents interface term between dipole and monopole terms. The dipole term has magnetic quantum number ($m = 1$) dominates but so that the interference with the monopole ($m = 0$) is small. Therefore, the three-body effect of the electron emission cross section has a broad angular distribution governed by the $\sin^2 \theta$ term of equation (11).
3. Result and Discussion

In order to solve equation (10) to calculate DDCS; at first we calculated the initial state wave function of ground and excited state of the target by solving Schrodinger equation with one electron potential. The phase shift \( \delta_i \) calculated by using partial wave method \(^{[14]}\).

Figure (2) shows the angular distribution of DDCS for electron emission in \( \text{Ar}^{18+} \) (95 MeV/u) + Li (ground state \( 1s^2 \ 2s^1 \)) for different emission energies. In this figure, the probability of emission for electrons in high energies are weak because of the DDCS for this emission is small but the probability of emission for electrons in low energies are strong because of the DDCS to this emission has high value.

Also Figure (2) shows the contribution of the electrons from two orbitals \( 1s \) and \( 2s \). The contribution of \( 2s \) orbital is larger than contribution of \( 1s \) orbital at emitted energy \( \epsilon = 10 \text{ eV} \). But \( 1s \) orbital contribution larger than \( 2s \) orbital contribution at emitted energies \( \epsilon = 30 \text{ eV}, \epsilon = 100 \text{ eV} \) and \( \epsilon = 300 \text{ eV} \).

![Figure (2): Angular distribution of DDCS for electron emission in Ar\(^{18+}\) (95 MeV/u) + Li (ground state 1s\(^2\) 2s\(^1\)).](image)

Figure (3) shows the sum of 1s and 2s orbitals of DDCS for electron emission. The value of DDCS for electron emitted in low energies larger than DDCS for electron emitted in high energies. This result agrees with soft collision which three-body effect depends on it.
Figure (4) shows the angular distribution of DDCS for electron emitted in $e = 10\ eV$ energy from 1s, 2s and 1s + 2s orbitals for different incident ion energies. This figure shows DDCS increasing with ion incident energies (low incident energies mean large soft collision).

Figure (4) shows the angular distribution of DDCS for electron emitted from outer shell of Alkali atoms in emitted energies $e = 100\ eV$ and $e = 100\ eV$.

Figure (3): Angular distribution of DDCS for electron emission of the sum of 1s and 2s orbitals contribution for different emission energies.

Figure (4): Angular distribution of DDCS for electron emitted in 100 $eV$ energy from ground state of Li at different incident ion energies.
Figure (5): Angular distribution of DDCS for electron emitted from outer shell of Alkali atoms in emitted energies $\epsilon = 10 \text{ eV}$ and $\epsilon = 100 \text{ eV}$.

Figure (6) shows the angular distribution of DDCS for electron emitted from excited shell 3s of Li atom and comparing with ground state 2s of Li atom for different emission energies. Also in this figure the DDCS for electron emitted from ground state 2s is larger and less brooding than excited state 3s for all emitted energies of electrons.

Figure (7) shows the probability of electron emission from excited state 3s in high emission energies is smaller than emission energies in low emitted energies of electron form Li atom.

Figure (8) shows the angular distribution of DDCS for electron emitted in $\epsilon = 10eV$ energy from excites state of Li 3s for different incident ion energies.

Figure (9) shows the angular distribution of DDCS for electron emission from first excited states of Alkali atoms for emission energies $\epsilon = 10 \text{ eV}$ and $\epsilon = 100\text{ eV}$. From this figure the probability of emission decreasing with emitted energies.
Figure (6): Angular distribution of DDCS for electron emitted from excited shell 3s and ground state 2s of Li atom for different emission energies.

Figure (7): Angular distribution of DDCS for electron emitted from excited state 3s for different emission energies form Li atom.
Figure (8): Angular distribution of DDCS for electron emitted in $\epsilon = 10\text{eV}$ energy from excited state $3s$ for different emission energies form Li atom.

Figure (9): Angular distribution of DDCS for electron emitted first excited states of Alkali atoms for emission energies $\epsilon = 10\text{ eV}$ and $\epsilon = 100\text{eV}$. 
4. Conclusion

1- Dipole term has magnetic quantum number \( m = 1 \) is dominated but the term with magnetic quantum number \( m = 0 \) is small, also interference term with dipole is small.
2- 2s orbital contribution is larger than 1s orbital contribution at low emission energies but 1s orbital contribution is larger than 2s orbital contribution at high emission energies.
3- DDCS decreasing with incident energy at the same emission energies.
4- DDCS of electron emission from outer shell \( (n)s \) is smaller than excited shell \( (n+1)s \) in Alkali atoms.

5. References

[1] J. Blieck, X. Fléchard, A. Cassimi, H. Gilles, S. Girard, and D. Hennecart, Review of Scientific Instruments 79, 103102 (2008).
[2] A. D. Ulantsev, J. Phys. B: At. Mol. Opt. Phys. 41, 165203 (9pp) (2008).
[3] A. D. Ulantsev, BULLETIN OF THE LEBEDEV PHYSICS INSTITUTE Vol. 34 No. 8 (2007).
[4] P. Vermaa, P.H. Mokler, A. Bräuning-Demian and C. Kozhuharov, Journal of Physics: Conference Series 388, 082008 (2012).
[5] S. Kadol, S. Kajita, Y. Iida, B. Xiao, Plasma Science and Technology, V01.6, No.5, Oct. 2004.
[6] S. T. Manson, L. Tobure, D. H. Madison, and N. Stolterfoht, Phys. Rev. A12, 60( 1979).
[7] N. Stolterfoht, J. Y. Chesnal, M. Grether and J. A. Tanis, Phys. Rev. A59, 1262(1999).
[8] N. Stolterfoht, Nuclear Instruments and Methods in Physics research, B145, 13(1999).
[9] L. Sarkadi, Nuclear Instruments and Methods in Physics research, B205, 533(2003).
[10] A. S. Davydove: “Quantum Mechanics”, Progmon press Ltd., printed in Great Britain, pp 487(1971).
[11] M. Inkuti, Rev. Mod. Phys. 43, 297(1971).
[12] M. R. Fiori, Ginetti Jalbert C, E. Bielschowsky and W. Cravero, Phys. Rev. 64, 012705(2001)
[13] T. F. M. Bonson, and L. veriens, Physica, 47, 307(1970).
[14] L.I. Shiff, “Quantum Mechanics”, (McGraw-Hill, NewYork, 1968), 3rd ed.