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by Asep Yoyo Wardaya

Advances in Physics Theories and Applications
ISSN 2224-719X (Paper) ISSN 2225-0638 (Online)
Vol.71, 2018

The Effect of Debye Sphere Potential on Electron Scattering by Ions in Tokamak using Born Approximation

Achmad Fajar Putranto[1] Muhammad Nur[1,2*] Asep Yoyo Wardaya[3]

1. Department of Physics, Faculty of Sciences and Mathematics, Universitas Diponegoro, Jl. Professor Haji Soedharto SH, Tembalang, Semarang, Jawa Tengah 50275, Indonesia
2. Center for Plasma Research, Universitas Diponegoro, Jl. Professor Haji Soedharto SH, Tembalang, Semarang, Jawa Tengah 50275, Indonesia
3. Master Program of Energy, School of Post Graduate Studies, Universitas Diponegoro, Jl. Imam Bardjo SH No. 5, Semarang, Jawa Tengah 50241, Indonesia

* E-mail of the corresponding author: m.nur@undip.ac.id

Abstract

Scattering in plasma is caused by Debye sphere potential effect in the aftermath of the changes in plasma species density to form Debye sphere. In Debye sphere, the scattering of electron by ions occurs in multiple ways (multiple scattering) as the amount of ions in Debye sphere. The perceived kinetic energy of electron is dominated by thermal perturbation that is affected by temperature so that the greater temperature thus the greater kinetic energy of the projectile particle. In tokamak plasma condition, it can be assumed that the kinetic energy of electron is much greater than the perceived potential energy of electron due to the ions Debye sphere potential thus Born approximation can be used. By using mathematical condition of Born approximation validity, it is obtained that the limit of electron multiple scattering by ions in which Born approximation is still valid is 3 times multiple scattering. Furthermore, it was found that the differential cross-section for electron scattering by ions is large at small angle scatterings $0° < \theta < 90°$ and small at large angle scatterings $90° < \theta < 180°$ which means that the form of potential interaction is not a Coulomb potential interaction but Debye sphere potential interaction that mathematically form Yukawa-like potential because the scattering occurs much more frequently at relatively long distance in which the scattering still occurs. It is obtained that the total cross section for electron scattering by ions is 2.81×10^{-10} m^2.

Keyword : Plasma, Debye sphere, Scattering, Multiple scattering, Born approximation

1. Introduction

In general, plasma is an ionized gas composed of a set of charged and neutral particles with degrees of ionization $0 < \alpha \leq 1$. Plasma in tokamak fusion reactor is a hot plasma which is in fully ionized state ($\alpha = 1$) so that it is only composed of a set of electrons and ions (Goldston 1995). In the plasma there is a thermal interaction that causes a set of electrons and ions moving at a certain speed then there is an electrical interaction that causes scattering among the charges that one of which is the scattering of electrons by ions (Bellan 2004).

In many particle systems, the observation of scattering will be more accurate when using multiple scattering (Guswantoro *et al.* 2014) then projectile particle can be assumed to be radial wave scattered in all directions by target particles (Sakurai 1994). The observation of electron scattering by ions is a microscopic review with maximum distance is at Debye sphere radius (Bittencourt 2004). Previously, there have been many researches related to scattering both theoretically and experimentally. The experiments were first performed by Rutherford and continued theoretically by S.Goudsmit and J.L. Saunderson (1939) and Moliere and H.A Bethe (1953). They studied the scattering of a charged particle system using multiple scattering. In addition, the electron scattering on relativistic conditions had been studied by Frankel *et al.* (1979).

Previously, the multiple scattering of electron by ions in plasma had been done. This work examined multiple scattering of electrons by all the ions in Debye sphere using Born approximation without examining the validity of Born approximation itself. It assumed that the electron scattering by all ions within Debye sphere. The mathematical approach which is used to solve second-order differential equation of Debye sphere potential using the Cartesian coordinates condition (Guswantoro *et al.* 2014).

There will be a research on multiple scattering of electron by ions due to the Debye sphere potential effect on tokamak conditions using Born approximation. The physical quantities to be sought from this research are the potential forms of scattering in Debye sphere, the scattering differential cross section of electron by ions, and the total scattering cross section of electron by ions. In addition, Born approximation validity (Sakurai 1994) will be tested on the multiple scattering reviews that can be studied in tokamak.

2. Method

The method of this study is using literature study, making assumptions, equation development and derivation. To validate the model using secondary data obtained from physical quantities of plasma in tokamak (Sips *et al*. 2005; Aymar *et al.* 2002).

In this case, there are a number of assumptions, i.e. : (1) plasma in a static condition (independent of time), (2) analyzing scattering in plasma using Debye sphere model, (3) the test charge in Debye sphere is an electron, (4) electron scattering by ions is due to Debye sphere potential, and (5) Debye sphere potential is a cumulative electric potential inside Debye sphere that causes the electron to be scattered by the potential in multiple terms.

In order to get the total scattering cross section in tokamak, it started from determination of the density form of a set of screening particles surrounding the test charge; determine potential scattering equation, determine validity of Born approximation to the number of multiple scattering in tokamak, determine scattering amplitude by using Born approximation, determine scattering differential cross section, and finally it is obtained the total scattering cross section of electron by ions in tokamak. The obtained potential energy equation is then compared to the result of potential energy by Guswantoro *et al*. (2014).

3. Result and Discussion

3.1 Potential Scattering in Plasma

The obtained potential energy of electron because of the Debye sphere potential is

$$V(r) = \frac{N_i q^2}{4\pi\varepsilon_0 r} e^{-r/R} \qquad (1)$$

Ni is the amount of electron scattering by the ions in Debye sphere. To determine the value of N_i then it tested the validity of the Born approximation derived from the Lipmann-Schwinger equation and obtained $N_i = 3$.

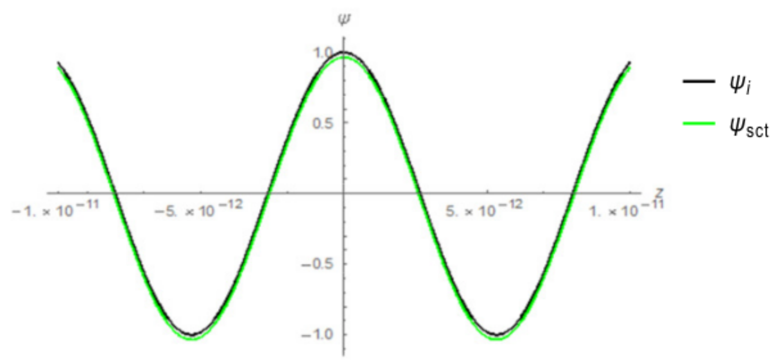

Figure 1. Comparison between the graph of incoming wave (ψ_i) and multiple scattered wave (ψ_{sct}) where total multiple scattering is equal to 3 ($N_i = 3$).

In Figure 1 it can be seen that there is very small change in wave function before and after scattering which means there is a very small perturbation on the incoming wave when through the potential scattering. Very small perturbation at once proves that Born approximation is valid on that condition.

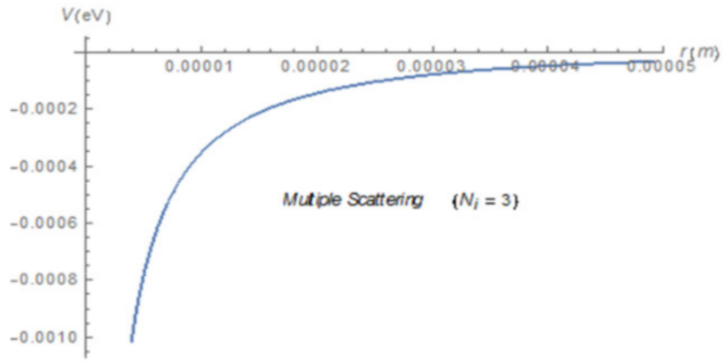

Figure 2. The potential energy of electron multiple scattering ($N_i = 3$) by ions in tokamak condition.

Figure 2 shows the graph of potential energy $V(r)$ to the distance from the center of Debye sphere r at $N_i = 3$. There is no characteristic difference from single scattering and multiple scattering in the Debye sphere because it is only distinguished by the value of N_i, which can be understood by the amount of related scattering charges that is affect the potential energy of each scattering. The more scattering charges then the greater potential energy of scattering.

Based on the study of multiple scattering in plasma had conducted by Guswantoro (2014), Debye sphere potential energy equation is

$$V_c(r) = -\frac{n_i q^2}{6\varepsilon_0}(3R^2 - r^2)e^{-r/R} \quad (2)$$

There is a very significant difference to the results of Figure 2 started from the graphic (see Figure 3) form which has relatively smaller degree of curvature and much larger potential energy value. This is due to differences in assumptions about the Debye sphere potential; and on his research the Born approximation is used on the entire amount of charge scattering in Debye sphere with $N_i = 8{,}45 \times 10^{22}$ which has not been tested for its validity.

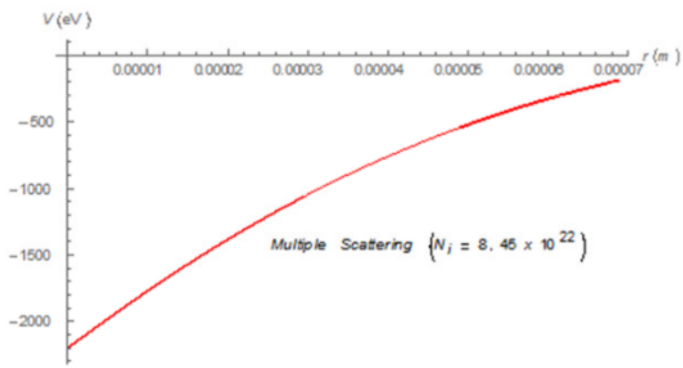

Figure 3. The potential energy of electron multiple scattering by ions in tokamak conditions based on the research equation by Guswantoro (2014).

3.2 The Scattering Cross Section of Electron by Ions in Tokamak Conditions

The differential cross section obtained with absolutely squaring the scattering amplitude equation which is obtained using Born approximation as follows,

$$\frac{d\sigma}{d\Omega} = \frac{{N_i}^2 q^4 R^4 \mu^2}{4\pi^2 {\varepsilon_0}^2 \hbar^4} \frac{1}{\left(1 + 4k^2R^2 \sin^2\left(\frac{\theta}{2}\right)\right)^2} \quad (3)$$

by subtituting the physical parameters value in tokamak conditions to the equation (3) so that resulting the graph as follow

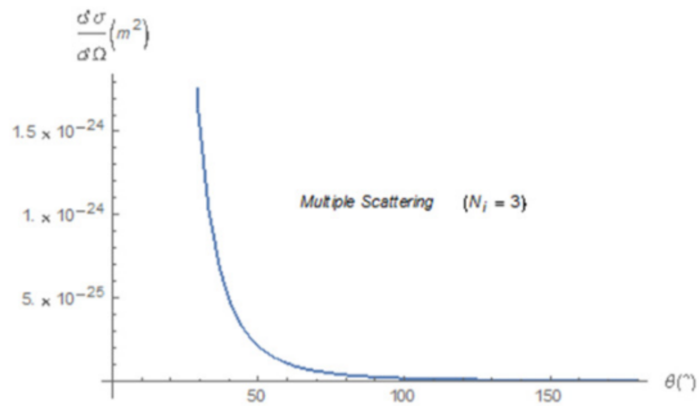

Figure 4. The differential cross section of electron multiple scattering (*Ni* = 3) by ions in tokamak conditions.

In figure 4 it can be seen the differential cross section value is high at the small angle scattering in range of $0^\circ < \theta < 90^\circ$. This is in accordance with the conditions in the plasma that most of the scattering occurs at a small angle and the smallest value at the time of scattering angle commonly known as inverse scattering. It can be seen that the differential cross section value is very small at large angle scattering $90^\circ \leq \theta \leq 180^\circ$ which states that the occurence probability of scattering at large angle scattering is very small.

By integrating equation (3) to the total solid angle then obtained the following total cross section equation.

$$\sigma = \frac{{N_i}^2 q^4 R^4 \mu^2}{\pi {\varepsilon_0}^2 \hbar^4} \left[\frac{1}{(1 + 4k^2R^2)}\right] \quad (3)$$

By substituting related parameters value in equation (4) so that obtained the maximum value of multiple scattering in Debye sphere at tokamak conditions where Born approximation is still valid is equal to 2.81×10^{-10} m^2.

4. Conclusion

The maximum limits of Born approximation to the analysis of electron multiple scattering by ions in tokamak conditions is 3 times of scattering. It is obtained the potential energy of scattering is always negative at the range of $0 < r \leq R$; it shows that the potential value in the Debye sphere is positive and depends only on the distance with the negative projectile charge particle. Then the value of differential cross section is high at small angle scattering in range of $0^\circ < \theta < 90^\circ$ and the differential cross section is small (approximately zero) at large angle scattering in range of $90^\circ \leq \theta \leq 180^\circ$. The results are consistent with the scattering conditions of the plasma that are largely located at small angle scattering which shows that on the electron scattering by ions in the plasma, instead of dominated by Coulomb potential interaction it is dominated by Debye sphere potential interaction which mathematically form Yukawa potential-like. And it is obtained that the maximum of total multiple scattering cross section by ions in the Debye sphere at tokamak conditions where Born approximation is still valid that is equal to 2.81×10^{-10} m^2.

Acknowledgement

The author give gratefully thanks to group of researcher in the CPR (Center for Plasma Research).

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PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5