

Graduate School of Physics, Department of Science and Engineering, Meisei University

Seiji IKEGAMI

### Abstract

Multiple scattering involves repetitive binary collisions between a projectile and target atom. The scattering potentials are obtained by a quantum mechanical treatment, while the actual scattering with incident particle and target matter is dictated by classical methods.

Studies of small angle multiple scattering were performed as early as the 1920s by Bothe [1] and Wentzel [2]. In the following decades, many theoretical and experimental investigations of multiple scattering were undertaken; a 1963 review by Scott details these early efforts [3]. Recent developments in multiple scattering theory have been reviewed by Sigmund in 2004 and 2014 [4]. The most useful theory to come from nearly a century of work may be the Sigmund–Winterbon (SW) model [5].

SW theory uses the differential scattering cross section constructed by Lindhard et al. [6]. Lindhard's cross section was treated by means of an impulse approximation. The importance of Lindhard's result is the agreement of the cross section under the small angle approximation in the absence of a small angle treatment. This agreement is confirmed using a power law potential for the scattering potential. Our conclusion is that the small angle limit is relatively weak in the SW model.

After decades of progress, multiple scattering is still the subject of much research. Relatively recent papers were written by Arista et al. [7, 8] employed a slow proton as an incident particle and showed large differences between theoretical and experimental results. Additionally, Arista et al. have recently done theoretical studies of an ion beam entering a free electron gas [9, 10].

Biological and medical applications of multiple scattering include structural imaging of cells using nuclear microscopy [11, 12]. For example,

cancer cells and fibrous tissue have been imaged, and heavy ion beam bombardment is used in the medical treatment of cancer [13, 14].

In the present study, we report a method to determine the screening length and the results obtained from this method. Determination of a suitable screening length is especially important in surface physics research [15]. Theoretical reproduction of experimental results using a single screening length has not yet been accomplished. In the present study, we derived a new screening length based on the Thomas–Fermi–Moliere potential. The present screening length can reproduce some experimental results. Major features of the present screening involve the charge state effect of the projectile, which is realized by using Kaneko’s screening length for single atoms [16]. Our theoretical screening results agree well with experiments for light projectiles and for relatively heavy targets. Small angle scattering indicates a relatively large impact parameter; however, we performed a Maclaurin series expansion to obtain the present screening length, which corresponds with a small impact parameter. Nevertheless, the experimental and theoretical results were in good agreement because the small angle limit is somewhat weak in the SW model, as mentioned above.

Furthermore, the present study introduced energy loss effects into the SW model. Pioneering work was done by Valdes and Arista (VA) on considering energy loss in the SW treatment [17]. However, the VA model treated only electronic energy loss and treated the effects of energy loss and target thickness independently. Within our model, we considered both nuclear energy loss and treated energy loss as a function of target thickness. We employed the Kaneko model [18] to describe the electronic energy loss and the Lindhard method [6] to describe nuclear effects. Electronic energy loss as a function of target thickness was obtained exactly. The nuclear energy loss was obtained as a function of a rough approximation of the target thickness. Results obtained from this model show that the energy loss effect caused by nuclear stopping cannot be neglected in the low projectile energy regime because nuclear stopping is more dominant than electronic stopping (results obtained for low incident particle energy of 27 keV). We therefore conclude that our approach is an improvement over the VA model.

Moreover, we constructed a switching model that includes the nuclear and electronic stopping effects in one formula. While the model is based on a very rough approximation, its solution can be obtained exactly. One weakness of the present model is the separation of the nuclear and electronic regimes. The regime where nuclear effects dominate corresponds to very thin target thicknesses. Hence, our model has a numerical calculation problem. However, from a theoretical point of view, a model that can be solved exactly would be beneficial.

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