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Classical Approximation for Ionization by Heavy Particle Impact

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In this paper, we examine the utility of the classical binary approximation proposed by Gryzinski[1] in predicting the ionization of atoms by heavy particles, notably protons. Our aim was as much a delineation of the classical binary approximation as an evaluation of its utility.

The method is based on a knowledge of the differential cross section, $\sigma^{eff}_{\Delta E}(v_1 v_2)$, for the exchange of energy ΔE in the lab frame between two charged particles of unequal mass, averaged over all velocity orientations of one particle. The ionization cross section for protons impinging upon an atom is then given by

$$\sigma_{ion} = \sum_{n_i} n_i \int_{U_i}^{E_1} \sigma^{eff}_{\Delta E}(v_1, v_{2i})\, d\Delta E \qquad (1)$$

where n_i is the number of electrons having ionization energy U_i and E_1 is the incident proton energy. The resultant cross section is then to be averaged over the velocity distributions of the bound electrons, $f(v_{2i})dv_{2i}$.

Our specific contributions are: (a) the use of the exact expressions for $\sigma^{eff}_{\Delta E}(v_1, v_2)$, avoiding any approximation (these have been recently made available[2] in closed form, and are easily integrated to give the total cross section); (b) in the case of ionization of hydrogen

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by proton impact, the use of the quantum mechanically correct velocity distribution for the bound electron.

The sensitivity of the Gryzinski approximation for inelastic atomic cross sections to velocity distributions is dramatically illustrated by proton ionization of hydrogen. This is in contrast with ionization by electron impact, where even the assumption $f(v_2) = \delta(v_2 - \sqrt{\frac{2U}{m_e}})$ gives cross sections at all accurately measured incident energies which in hydrogen are within a factor of about 3 of experimental values.[3] For protons, this assumption would predict a cross section which is zero for incident energies less than $\sim 78U$, $(\frac{v_1}{v_2} < (\frac{\sqrt{2}-1}{2} + \frac{m_e}{m_p}\frac{\sqrt{2}+1}{2}))$ or about 1 keV. This is due to the relative inability of a heavy particle to transfer large energies to a lighter one.

Despite this sensitivity, the cross sections given by (1) even with the δ-function distribution are found to be quite good approximations to the experimental values for energies above $E_1 = 78U$. In fact, the predicted cross sections differ from the experimental by less than a factor of 2 or 3, very similar to the results found by Bauer and Bartky[4] for electron ionization. Ionization of the noble gases by protons and other assorted heavy particle ionizations have been examined and comparison with experiment will be given where possible. Both delta function and hydrogenic electron velocity distributions have been used. A comparison of electron and proton ionization for equal velocities also will be given as well as an examination of ionization from a sequence of excited states. It is found that for a given velocity of the bound electron, the heavy particle ionization cross section scales readily with ionization energy.

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References

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