Charge transfer in proton-hydrogen collisions under Debye plasma

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(Received 7 November 2014; accepted 11 February 2015; published online 27 February 2015)

The effect of plasma environment on the $1s \rightarrow nlm$ charge transfer, for arbitrary $n$, $l$, and $m$, in proton-hydrogen collisions has been investigated within the framework of a distorted wave approximation. The effect of external plasma has been incorporated using Debye screening model of the interacting charge particles. Making use of a simple variationally determined hydrogenic wave function, it has been possible to obtain the scattering amplitude in closed form. A detailed study has been made to investigate the effect of external plasma environment on the differential and total cross sections for electron capture into different angular momentum states for the incident energy in the range of 20–1000 keV. For the unscreened case, our results are in close agreement with some of the most accurate results available in the literature. © 2015 AIP Publishing LLC.

[http://dx.doi.org/10.1063/1.4913474]

I. INTRODUCTION

Effects of hot, dense plasmas on the electron capture processes have received considerable interest in the recent years (and further references therein), since these processes have wide applications in many areas of physics, such as modeling of laboratory fusion, astrophysical plasmas, as well as in basic researches in astrophysics, atomic physics, and plasma physics. Of particular interest is the problem of electron transfer in proton-hydrogen collision, since this is one of the simplest types of rearrangement collisions and plays an important role in many astrophysical environments. Apart from developing our understanding regarding a basic charge transfer process, collision cross section data for capture into various excited states are frequently required for plasma diagnostics and studies in astrophysics. Hydrogen, the most abundant element in the Universe, exhibits its existence through the production of emission (or absorption) lines, either via the recombination of protons with electrons or the collisional excitation of hydrogen atoms by electrons or protons. In astrophysical regimes, where the collisional excitation of hydrogen atoms is relevant, the cross sections for the interactions of hydrogen atoms with electrons and protons are necessary for calculating line profiles and intensities. In particular, at relative velocities exceeding approximately 1000 km/s, collisional excitation by protons dominates over that by electrons.

In the environments of dense and high-temperature plasmas, such as in inertial confinement fusion plasmas and astrophysical plasmas of compact objects, the range of the electron Debye length $\lambda_D$ is known to be $\lambda_D \lesssim 10a_0$, where $a_0$ is the first Bohr radius of the hydrogen atom, since the electron density $N_e$ and temperature $T_e$ are around $10^{20}$–$10^{23}$ cm$^{-3}$ and $10^7$–$10^9$ K, respectively. These plasmas can be classified as Debye plasmas or weakly coupled plasmas. In weakly coupled plasmas, long-range self-consistent interactions (described by the Poisson equation) dominate over short-range two-particle interactions (collisions). In other words, the ratio of the potential energy to the average kinetic energy, called the coupling parameter ($\Gamma$), is much less than unity. There is a wide class of laboratory plasmas in which these conditions are also fulfilled. The Coulomb interaction screening in weakly coupled plasmas is a collective effect of the correlated many-particle interactions, and in the lowest particle correlation order it reduces to the Debye–Hückel potential or static screened Coulomb potential (SSCP) of the form

$$V(r) = \left(\frac{1}{r}\right)e^{-\theta pr} \text{ (in a.u.)}$$

where $\theta$ is the screening parameter. In the Debye model of screening, the screening parameter $\theta$ is related to the Debye length $\lambda_D$ by means of the relation $\lambda_D = 1/\theta = [KT_e4\pi e^2N_e]^{1/2} = \varepsilon_T/\epsilon_0$, where $e$ is the electronic charge, $N_e$ is the plasma-electron density, $K$ is the Boltzmann constant, $T_e$ is the electron temperature, $\varepsilon_T$ is the thermal velocity, and $\epsilon_0$ is the plasma frequency. So, the Debye-Hückel model can be employed to adequately describe the screened interaction potential in classical weakly coupled plasmas.

In this paper, we make an attempt to study the effects of screening of Debye plasma on the simplest charge transfer reaction

$$p + H(1s) \rightarrow H(nlm) + p,$$

for arbitrary $n$, $l$, and $m$. Most of the investigations to study the plasma screening effect on the above process are semi-classical and restricted for low-lying excited states such as $n \leq 2$. To the best of our knowledge, there exists no collision cross section data for arbitrary $n$, $l$, $m$, as well as detailed nature of the differential and total cross section is hitherto unknown. But, as said earlier, collision cross section data for capture into various excited states are frequently required for plasma diagnostics and studies in astrophysics. In vacuum, the scattering of proton from the hydrogen atom has been extensively studied, both theoretically and experimentally (and further references...