Collisional radiative recombination $Ar^+ + e^- + e^-$ in low temperature plasma

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The process of collisional radiative recombination in low temperature plasma was studied using cryogenic Flowing Afterglow with Langmuir Probe apparatus experiment (CRYO-FALP II). The three body recombination involves two electrons and ion and it depends strongly on plasma temperature ($\sim T^{-4.5}$). In present study the ternary recombination rate coefficient was measured in range from 55 K up to 180 K. Because of strong temperature dependence we monitor the plasma temperature by measuring the characteristic time of diffusion.

A ternary recombination of atomic ion with two electrons may compete with a binary radiative recombination in some types of plasma. This ternary process involves positive ion and two electrons from plasma and it is called the Collisional Radiative Recombination (CRR). The theoretical description of this process was formulated by Bates et al. [1]. Stevefelt et al. [2] gave the following analytical formula for effective apparent binary recombination rate coefficient:

$$\alpha_{\mathrm{CRR}} = 3.8\times10^{-9} T_{\mathrm{e}}^{-4.5} n_{\mathrm{e}} + 6.0\times10^{-9} T_{\mathrm{e}}^{-2.18} n_{\mathrm{e}}^{0.37} + 1.55\times10^{-10} T_{\mathrm{e}}^{-0.63} \mathrm{cm}^3\mathrm{s}^{-1} \qquad (1)$$

From the equation (1) we can see that the contribution of ternary process increases with grow of plasma concentration n_{e} or decline of electron temperature T_{e}. The CRR was previously studied in temperature range of 300 to 4000 K [3,4,5].

For this study we recently constructed a flowing afterglow apparatus with Langmuir probe and cooling system (Cryo-FALP II) [6,7]. Using closed cycle helium refrigerator we can reach temperature of flow tube down to 55 K. The discharge is ignited in pure helium at 300 K in uncooled section of the flow tube. Further downstream, argon was introduced into the flow tube to convert helium ions and helium metastables to argon ions. The concentration of argon was carefully chosen to be high enough to convert helium metastables efficiently but low enough to avoid formation of Ar_2^+ ions [8]. The Ar^+ dominated plasma carried by helium flow enters the cryogenic section. In this section neutral gas is rapidly cooled and Ar^+ and electrons are cooled by collisions with He atoms. The decay of plasma in this section is driven by ambipolar diffusion and by recombination. To obtain recombination rate coefficients the decay of plasma along this section is monitored by axially movable Langmuir probe. The temperature dependency of ternary rate coefficient is very steep so the precise determination of temperature of plasma is crucial.

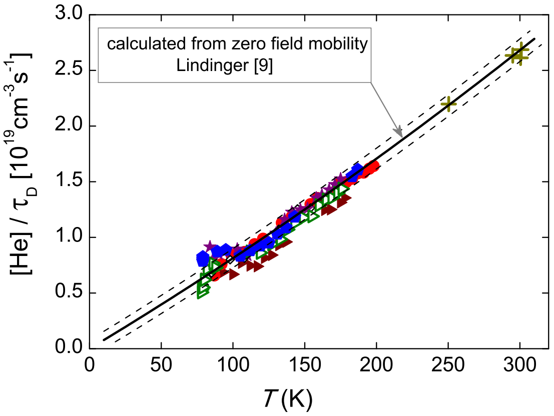

Fig. 1: The measured diffusion losses characterised by $[He]/\tau_D$ are compared with values calculated from zero field mobility data [9]. The dashed lines depict theoretical values for ±10 K from temperatures measured on the flow tube wall.

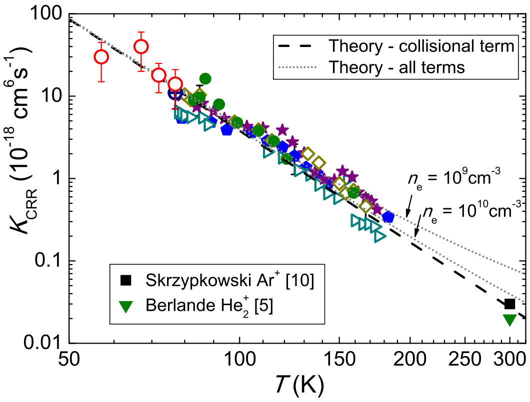

Fig. 2: The rate coefficient of ternary recombination K_{CRR} and its dependence on temperature. The measured values agree with predicted dependence [2] in the entire temperature range. The values at 300 K originate from [5,10].

We monitor temperature of plasma by evaluating diffusion losses along the flow tube and comparing it with model which use zero field mobility measured in drift tube experiments [9]. Actually we compare measured value of [He]/τ_D with value calculated for given temperature from corresponding zero field mobility. The measured and calculated dependencies are plotted in figure 1 and we can see excellent overlap indicating that the temperature of the decaying plasma is equal to the temperature of the buffer gas. From a measured electron density decays we evaluated rate coefficient of ternary recombination $K_{\mathrm{CRR}} = \alpha_{\mathrm{CRR}}/n_e$. The obtained values of K_{CRR} are plotted in figure 2. At our conditions the main contribution is introduced by the first term of equation (1).

We can conclude that the measured dependence of K_{CRR} on temperature for atomic ions agrees very well with prediction from [2]. It shows that analytical formula (1) is valid even for low temperatures. The CRR process may play an important role in low temperature plasmas even at moderate electron concentrations. The absolute uncertainty of measured K_{CCR} values is typically 30%. The main source of error is determination of plasma concentration.

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