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IMPACT OF COLLECTIVE EFFECTS ON PLASMA IONIZATION

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Abstract. Plasma can be produced using different schemes based on ionization processes of a neutral gas. Recently, it was demonstrated that due to collective effects the ionization potential of chemical elements can be changed particularly for dense plasmas. We investigated this characteristic for mono-atomic gases and found that the critical density for which these effects are significant is $n_o \sim 10^{13}\,\mathrm{cm}^{-3}$. The latter depends on atom's ionization energy. It is also found that this effect can only be observed for a certain range of density and temperature related to the first ionization potential of the chemical element.

Keywords: ionization, Saha equation, neutral plasma..

1. Introduction

Collective effects play a crucial role in plasma, not only because they give the possibility to distinguish between a neutral gas and a charged one, i.e. plasma. Indeed, when the rate of ionized atoms to neutral ones exceeds 10^{-4}, the particles inter-distance becomes short enough that the Coulomb interaction between charged particles starts to be significant. Thus, collective effects are responsible of plasma response to small perturbation that gives rise to oscillations or waves.

Plasma can be produced from neutral gas by ionization processes such as electron impact, secondary emission and photo-emission. All these processes need to provide a minimum energy depending on the electron binding energy to the atom. However, in the presence of an external field such as the one created by charged particles surrounding a test ion, this energy is lowered. For quasi-neutral plasma in thermal equilibrium, the ground energy of a plasma species is lowering leading to the reduction of all ionization energies [1]. Based on statistical methods Ecker and Kröll have shown that the ionization energy is decreased when the density is above a critical value [2]. Stewart and Pyatt used a finite temperature Thomas-Fermi model to show that all ionization potentials are lower by Jk_B, where k_B is the Boltzmann constant, T the temperature and J is a parameter to measure the reduction of the ionization potential. The latter depends on the ion sphere volume to the Debye sphere volume ratio. However, this model neglects the fluctuations rise due to correlation between individual particles [3]. Moreover, In a Coulomb system such an ionization potential depression (IPD) occurs by continuum lowering associated to the thermodynamic ionization potential depression which can be used in modeling the equation of state [4]. The IPD has been found to have significant effect in dense aluminum plasma [5], atomic processes such as ionization/recombination [6] and in the dynamics of solid-density plasmas ionization [7].

Recently, Ciricosta et al. presented an experimental study and conduct a comparative investigation between Stewart-Pyatt and Ecker-Kröll models based on the use of short-pulse tunable x-ray free-electron lasers. For a dense hot plasma the IPD depression was significantly greater as predicted by Ecker-Kröll model [8]. In this work we investigate this model to find the critical density for specific temperature leading to a noticeable IPD in a given plasma. For that purpose we consider only mono-atomic gases and focus on the first ionization energy potential.

2. Ionization of Gases

To obtain a plasma, a neutral gas must have a certain amount of ionized atoms (molecules) which can be obtained when at least one electron is knocked out:

$$A \to A^+ + e$$

This can occur through different processes such as by electron impact when an electron beam penetrates the gas chamber. Whatever the process used to ionize an atom a minimum of energy have to be provided that is $E > eU_i$ (U_i is the first ionization potential and e is the elementary charge). The easiest why to achieve this is by increasing the temperature to provide the energy k_BT. Thus, if the gas density at t_o is n_o, at a given time the ion density is n_i, the Saha equation giving the balance equation between ion and neutral densities leads to

$$\frac{n_i}{(n_o - n_i)} = \frac{2}{n_e}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} e^{-eU_i/k_BT} \qquad (1)$$

where m_e and n_e stand for electron mass and density, respectively. We have considered only the case where one ion species of charge number $Z = +1$ is produced from an atomic element. For quasi-neutral plasma i.e.; $n_e = n_i$, to find the plasma density for a given temperature, one has to solve the following equation:

$$n_i^2 + Cn_i - Cn_o = 0 \qquad (2)$$

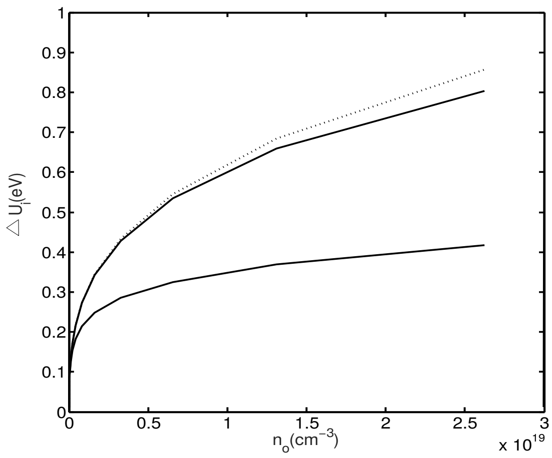

Figure 1. Energy associated to the potential lowering versus the gas density for two temperatures: 0.5 eV (dashed line) and 1 eV (solid line). The ionization potential is 4.34 eV (Potassium).

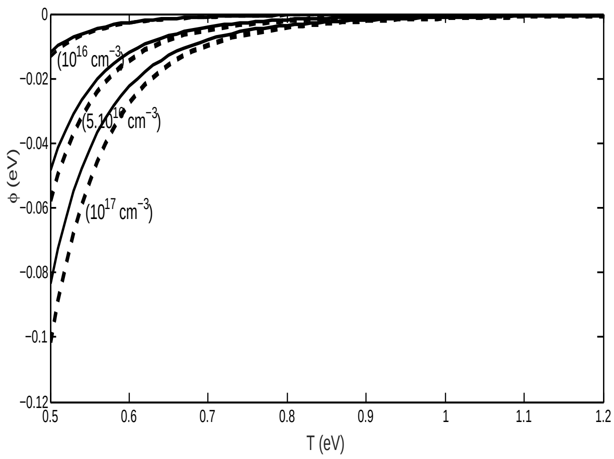

Figure 2. The plasma potential versus the temperature without IPD effect (solid line) and with IPD effect (dashed line). The parameter labeling the curves is initial density n_o.The ionization potential is 4.34 eV(Potassium).

The constant in this equation corresponds to $C = 2\left(2\pi m_e k_B T/h^2\right)^{3/2} e^{-eU_i/k_BT}$.
In a simple model that assumes an isolated atom and according to Bohr's theory, the ionization energy corresponds to

$$U_i' = \frac{13.6}{n^2} \quad \text{(eV)} \tag{3}$$

where n refers to the principal quantum number (shell number). However, in the presence of n_o particles, the potential U_i has to be corrected due the contribution of micro-fields which are important for charged particles. The latter, alter the potential shield leading to the reduction of Debye length. Thus, the ionization potential is lowered by an amount of [2, 8]:

$$\Delta U_i = e^2\left(\frac{8\pi}{3}n_i\right)^{1/3} \tag{4}$$

Let us emphasize on the fact that $U_i = U_i' - \Delta U_i = f(n_i)$, leads to a self-consistent problem.

3. Results and Discussions

We have plotted in figure 1 the amount of potential lowering versus the initial gas density for two different temperatures.
First, we note that the density is limited to 10^{19} cm^{-3} because beyond this value the plasma is very dense and quantum effects start to play an important role [9]. This is not included in the present model. The changes in the potential are significant when the gas density exceeds $\sim 5\times10^{13}$ cm^{-3}. The lower the density the higher the inter-distance between particles is, making the Coulomb interaction weak and turns out to cancel collective effects. For a higher density the plateau formation is associated to a saturation of the collective effects in the IPD, probably because other forces start to play a more important role which need to be included in the modeling of ionization potential calculation and in Saha equation. When the temperature increases, thermal motion dominates and collision becomes important leading to more fluctuations that are not included in the IPD models. However, we note that the IPD is more significant for higher temperature (solid line of figure 1 corresponds to $T = 1$ eV) because electron are less bounded to atoms. With free electrons the shift is more important due to collective effects. Such an effect can be depicted from figure 2 showing that the potential depression is higher for dense plasma. Beyond a certain temperature (~ 1.1 eV) the IPD effect can't be seen because neutrals are all almost ionized due to thermal energy. We note that the critical density obtained in this work $\sim 10^{13}$ (cm^{-3}) is very small compared to the value obtained by Lin *et al.* [5] ($\sim 10^{20}$ cm^{-3}) for two reasons: first we didn't consider a dense plasma as mentioned previously. Secondly, in their work the ion is highly charged (Z=+11), which it is not the case in this work. Moreover, the charge state and the density play a crucial role on the IPD rate. discrepancy found in different models calculating the IPD is considerably reduced with smaller density and charge number[2, 3, 10–12].

By considering the difference between ionization energy with and without IPD effect: $\Delta U_i > 10^{-2}$ eV, we have plotted the critical density versus the ionization potential for different chemical elements (Figure 3). At a low temperature ($T = 0.5$ eV), as the ionization potential is more important the critical density increases drastically from $U_i \geq 7.19$ eV (chromium). When this potential is more important, electrons of the outer atom shell are strongly bounded to the atom. The IPD must be more higher which is realized by reducing the inter-atomic distant. Thus, the critical

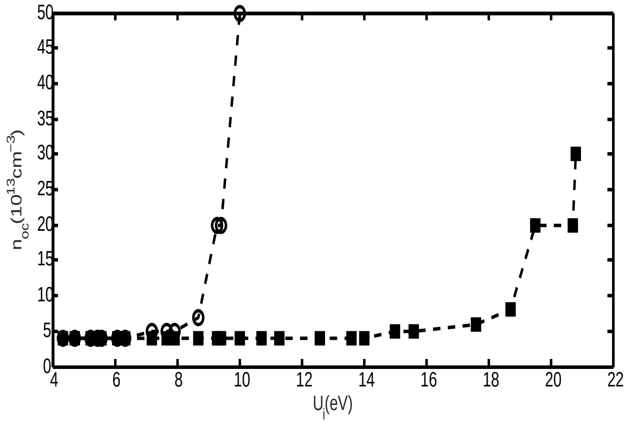

Figure 3. Critical density versus the ionization potential for T=0.5 eV (circle) and 1 eV(full triangle).

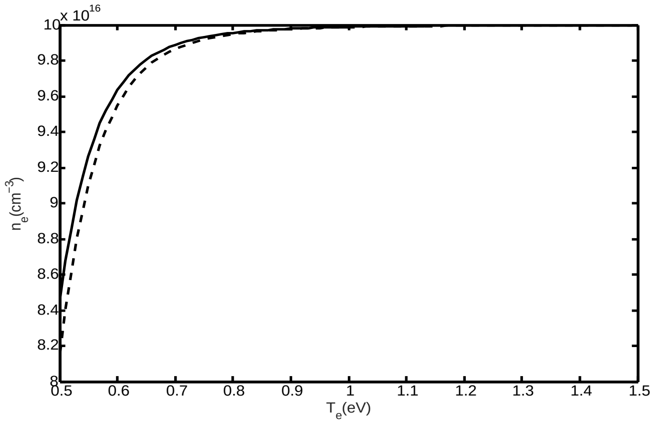

Figure 4. The difference between electron densities (with and without IPD effect) versus T .

density increases. We also note that this critical density is reduced when the temperature increases as a consequence of the atom random motion.
In figure 4 we have plotted versus the temperature, the difference between electron density when the IPD is included n'_e and the electron density without this effect n_e: $\Delta n_e = n'_e - n_e$. The lower is the first ionization potential, the higher the difference is. It is clear that plasma is easily produced for electro-positive elements. The temperature plays a crucial role in this process, there exists a specific temperature which maximize the density difference. Lower temperatures didn't ensure important ionization but higher ones hide the collective effect due to random motion.

4. Conclusions

We have investigated the effect of inter-atomic interaction on the ionization of mono-atomic gases by including ionization potential depression in ionization balance equation. The contribution of Coulomb inter-particles interaction was found to be significant for a critical density of the gas. This density depends both on the temperature and the gas ionization potential. Such an effect can only be observed for certain ranges of density and temperature. Lower temperature produce a weak partially ionized plasma while higher one dominates the ionization potential depression due to thermal energy that ionizes all neutral atoms. The density also reaches a saturation value because when it starts to be very high other physical effect have to be included to the model such as quantum effects.

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