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Influence of electron impact ionization on the efficiency of thermoemission ion source

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The electron impact ionization by accelerated thermionic electrons is included into the numerical model of thermoemission ion source. Mean free paths of atoms in the ionizer are comparable with the ionizer size at high working temperatures (3500 K). The dependence of the source efficiency on the ionizer temperature and the electron impact ionization cross-section is studied. In the case of substances having a small ionization coefficient ($\beta \ll 1$) the contribution of the electron impact ionization may be dominant at high temperatures and the predictions based on previous surface ionization model can be changed significantly.

1. Introduction

There is a variety of ion source types employed for electromagnetic isotope separation, ion implantation, and nuclear spectroscopy purposes, depending on particular needs. One of them is a thermoemission ion source (TIS), whose main features are: simple design, high working temperature in the range 2500–3300 K and small dimensions of an ionization chamber [1–3]. Ion sources of such a kind are still being developed and improved [4–7]. Their main advantage is high ionization efficiency and very small amounts of separated substance needed to obtain a stable ion current. Also the amount of impurities (like residual gas ions or multiple ions) in the extracted ion beam is very small. Moreover, the time the atoms stay in the ionization chamber is exceptionally short. Due to the above mentioned advantages, the thermoemission ion sources are used for on-line separation of short-lived isotopes produced by high energy proton beam irradiation of a target [8]. They could be also employed for negative ion production [9].

The main part of the TIS is a cylindrically shaped, semi-opened ionization chamber, also known as an ionizer. The ionizer is heated to working temperature by electron beams emitted from tungsten. During on-line experiments the ionizer is also the target bombarded by high energy proton beam. There are a lot of phenomena that occur in the TIS due to its high working temperature, e.g. surface ionization, thermal ionization and thermionic emission. This intricacy results in a lack of precise model of ion production in such a source.

The production of ions during the thermal desorption of atoms or molecules on the ionizer surface is known as surface ionization. This process is characterised by a quantity called the ionization degree α, which could be obtained from the Saha–Langmuir formula [10]. Another parameter $\beta = \alpha/(1+\alpha)$, known as an ionization coefficient, is also frequently used.

Thermal emission takes place when either particles of genuine ionizer material or diffusing particles of dopant (e.g. products of the above mentioned nuclear reactions) are emitted from the ionizer surface.

The hot surface emits also electrons (thermionic emission). The dependence of electron current density on the emitter temperature is given by the Richardson–Dushman formula. A typical energy of emitted electrons is $\overline{E} = kT$. At typical working temperatures ($\sim$3000 K) this energy is too small ($\sim$0.26 eV) for atoms to be ionized. On the other hand, the number of thermionic electrons having sufficient energy is negligible. However, it should be noted that the extraction field (EF) penetrates the ionizer near the orifice. Electrons are accelerated by that field and move deep into the ionizer cavity. They could gain energy larger than the ionization energy E_i of the substance under consideration. The presence of electrons having the ability to ionize in the TIS has been experimentally confirmed [11].

In our previous papers we presented both theoretical [12] and numerical [13] calculations of ionization efficiency taking into account the surface ionization only. The aim of this work is including the electron impact (EI) ionization (caused by thermionic electrons) into our model. A brief description of the numerical

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model is given in the paper. The influence of the ionizer temperature on source efficiency was under investigation in the frame of a model including the electron impact mechanism of ionization. Changes of the source efficiency for different values of EI ionization cross-section were also studied. The results of calculation for the realistic shape of the EF (flat extraction electrode) were presented. The limiting case of a homogeneous EF was also considered. Such field shape, almost impossible to obtain in practice, could result in the 'each ion' work regime [12,13].

2. Numerical model

The code follows trajectories of charged and neutral particles moving inside the ionizer. There is a flat extraction electrode (of the potential – V_{ext}) 2 mm far from the ionizer orifice. The simulation area is covered with the 3D Cartesian spatial grid. The cell dimensions are $\Delta x = 0.2$ mm and $\Delta y = \Delta z = 0.1$ mm. The grid has 100 nodes in y and z directions and 500 nodes in x direction (ionizer length $L = 80$ mm). The electrostatic potential distribution is determined by solving the Laplace equation. This is done using the successive over-relaxation technique [14]. Electric field is evaluated by numerical differentiation of the potential. Particles are emitted from the inner ionizer surface according to the cosine distribution of their velocity direction with respect to the normal. The values of initial velocities correspond to the temperatures in the range 2900–3500 K (0.25–0.30 eV). The equations of motion are solved using the 4-th order Runge-Kutta method [15]. When the particle hits the ionizer wall, the Monte–Carlo based subroutine decides whether the particle is ionized/neutralized or not, according to β parameter. Moreover, as it has already been mentioned, atoms could be ionized by impact of electrons emitted from the hot ionizer surface. It is possible only if the electron energy E_e is greater than the ionization energy E_i of the substance under consideration. Assuming that the density of electrons having energy greater than E_i is n_e and σ is the EI ionization cross-section [16,17], the mean free path the atom travels inside the chamber (until it is ionized by electron) could be calculated as:

$$\lambda = \frac{1}{n_e \sigma}. \quad (1)$$

The assumption has been made that the cross-section has a constant non-zero value only in the range from E_i up to some cut-off energy E_c. In other words, it is assumed that the probability of ionization by the electron having $E_e > E_c$ could be neglected. Electrons are accelerated by EF and directed deep into the ionizer. In the case of the realistic field from the flat electrode the simplifying assumption could be made that only thermionic electrons emitted from the cylindrical surface of the length l near the extraction hole could gain $E_e > E_i$. The value of l could be determined by analysing the potential distribution inside the ionizer. The EI ionization is possible almost in the whole volume of the ionizer except the region near the orifice, where electrons do not have sufficient energy. The density of electrons that have $E > E_i$ could be estimated by the formula

$$n_e = \frac{2lj}{er\bar{v}} \quad (2)$$

where j is the thermionic electron current density given by the Richardson–Dushman formula, r is the ionizer's radius, $\bar{v}$ is the mean velocity of electrons accelerated by the electric field and e is the elementary charge. The value of n_e could be derived in a very similar way also in the case of the homogeneous field ('each ion' regime).

Having λ calculated, another Monte–Carlo based subroutine calculates the path s_i each atom travels inside the chamber until it is hit and ionized by an electron. This is done according to the formula:

$$s_i = -\lambda \ln(RND), \quad (3)$$

where RND is the normal pseudorandom number. The EI ionization takes place when the atom path is larger than s_i, provided the atom stays in the region where the ionization is possible. The particle continues its journey until it leaves the ionizer. The code counts the number of ions N^* and neutral atoms N^o leaving the ionizer as well as calculates the ionization efficiency $\beta_w = N^*/(N^* + N^o)$.

3. Results

In order to determine the contribution of the EI ionization in β_w of the TIS mean free path of atoms inside the ionizer were calculated for different T using formulae (1) and (2). The results for the case of flat electrode ($V_{ext} = 1000$ V) are shown in Fig. 1. It could be seen that for high enough temperatures (3300–3500 K) λ is comparable to the ionizer length. Consequently, at high T the contribution from EI ionization could be significant. The λ value for the homogeneous EF of $E = 1000$ V/m is 2 orders of magnitude smaller compared to the flat electrode case. This is due to the greater n_e (electrons able to ionize are emitted from much larger surface of ionizer). Having λ worked out, the $\beta_w(\beta)$ dependencies were determined. The large number of 100 000 test particles representing atoms of $M = 250$ a.m.u. were employed.

Due to the fast increase of n_e with T one may expect that the contribution of the EI ionization to β_w also grows fast with T. The results presented in Fig. 2a and b (the case of flat electrode) confirm this expectation. Fig. 2a shows the $\beta_w(\beta)$ dependencies for kT from 0.25 eV up to 0.30 eV. The influence of T (and EI ionization) is larger for small β, especially for $\beta < 0.1$. Fig. 2b presents the relative change of β_w defined by the formula:

$$\delta = \frac{\beta_w - \beta_w^o}{\beta_w^o}, \quad (4)$$

where β_w^o is the source efficiency without EI ionization taken into account. One can see that for small β taking EI ionization into account increases the model predictions by 100% ($kT = 0.30$ eV).

The influence of σ value on β_w was also under investigation. The simulations were done for σ in the range from $2 \cdot 10^{-16}$ cm^{-2} up to

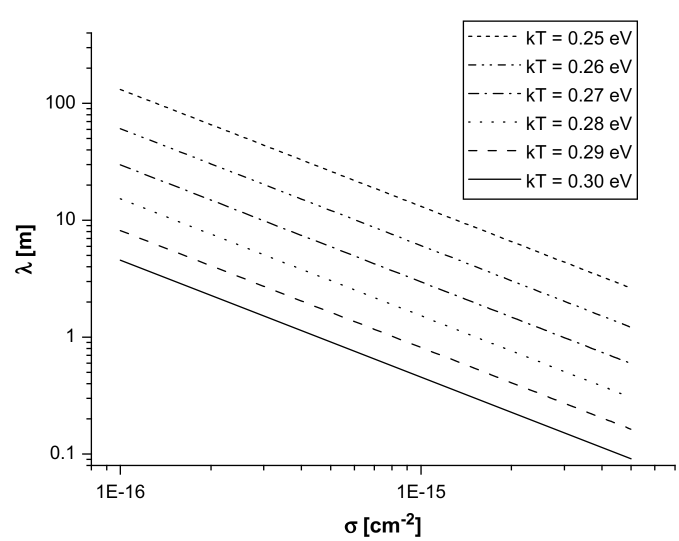

Fig. 1. Mean free paths of the atom inside the source (EI ionization). The case of flat electrode.