Positron transport in molecular gases in crossed electric and magnetic fields

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Positron transport in molecular gases in crossed electric and magnetic fields

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Abstract. Transport properties of positron swarms drifting and diffusing in neutral gases under the influence of crossed electric and magnetic fields are investigated using a multi-term theory for solving the Boltzmann equation and Monte Carlo simulation technique. In the presence of magnetic fields the number of transport properties is increased compared to the situation when the positron swarm is acted on solely by an electric field. Since the longitudinal and transverse components of the drift velocity show different sensitivities with respect to the strength of the magnetic field, it is found that the negative differential conductivity effect in a crossed field configuration can be controlled through the variation of the magnetic field strengths. Various diffusion tensor elements also exhibit different sensitivities with respect to the magnetic field and also with respect to the positronium (Ps) formation process.

1. Introduction

In the last few decades there has been growing interest for studying positrons both theoretically and experimentally [1]. One of the major motivational factors for this was the revolutionary improvement of buffer-gas, Penning Malmberg traps for positrons made by Surko and co-workers [2,3]. The improved positron traps have provided high-flux, low-energy positron beams and thus the new era of positron physics was born. Perhaps the first response came from the atomic physicists with the provision of accurate cross sections for positron interactions with different gases [4-7], which has opened the possibility to model the transport processes of positrons in neutral gases and soft-condensed matter [8-10, 11], with the principal idea of improving the positron based technologies such as those employed in positron emission tomography. In this paper we investigate the transport properties of positron swarms in neutral molecular gases in a crossed electric and magnetic field configuration. We investigate the positron transport in crossed electric and magnetic fields as possible applications may use combined fields to achieve a better control of properties of the ensemble [12]. It is well known from the recent comprehensive electron studies that the transport properties of electrons can be significantly affected by the magnetic field, particularly under conditions when the cyclotron frequency dominated the collision frequency [13]. Using these arguments as a background, we have been motivated to check the basic features of positron transport in electric and magnetic fields.

The transport properties of positron swarms moving in neutral gases have been studied using a multi-term theory for solving the Boltzmann equation [14, 15] and a Monte Carlo simulation technique [16]. Both techniques have been developed for studying the electron swarms in varying configurations of electric and magnetic fields under hydrodynamic and non-hydrodynamic conditions. Numerical codes have passed all well-established benchmarks with high accuracy levels. In the framework of recent positrons studies, however, special attention has been paid to the correct treatment of positronium (Ps) formation. Ps formation is a non-conservative process unique to positrons which often has a cross section larger than the cross sections for elastic and various inelastic collisions. The kinetic effects induced by the non-conservative nature of collisions manifest themselves as a difference between the flux and bulk transport properties [17]. It should be emphasized that the duality of transport coefficients has been systematically ignored in the majority of previous work in the plasma modeling community, and in related electron studies. The differences between the flux and bulk transport properties observed in positron transport are often more pronounced than those for electrons, particularly for those gases with a large Ps formation cross-section. One of the most important kinetic phenomena observed both in electron and positron transport is negative differential conductivity (NDC). This phenomenon can be defined as a decrease in drift velocity of the swarm with increasing driving electric field. Both the nature and the manifestation of this phenomenon are different for electrons and positrons. In case of electrons [18-20], NDC is present in both the flux and bulk velocity components while for positrons it has been observed only in the bulk drift velocity. The differences between flux and bulk drift velocities can be more than two orders of magnitude [8-10], while for electrons they are generally 15-20% [13, 14]. Also, NDC is much more pronounced for positrons than for electrons and it originates purely from the non-conservative nature of Ps formation. The interesting situation occurs when the inelastic channels start to open in the vicinity of the threshold of Ps formation. Sometimes, for example in nitrogen [9], the competition between these channels leads to the disappearance of NDC, even though the cross section for Ps formation is as high as it is for the gases with very pronounced NDC. In what follows these issues are illustrated and discussed for positrons in molecular hydrogen.

2. Transport in a crossed field configuration

In a crossed electric and magnetic field configuration the drift velocity has two components: the longitudinal $w_{\mathbf{E}}$ and transverse $w_{\mathbf{E}\times\mathbf{B}}$. These two drift velocity components behave in a completely different manner and, as a consequence, the NDC effect can be controlled by the magnitude of magnetic field. The diffusion tensor has five non-zero elements, which all exhibit different sensitivities with respect to magnetic field and also with respect to Ps formation process. The magnetic cooling effect has also been observed – the mean energy of the swarm is a decreasing function of the magnetic field for all electric field strengths considered in this work.

2.1. Magnetic cooling effect

The magnetic cooling effect is a well known phenomenon observed in electron transport in real [13, 21, 22] and model gases [23]. This phenomenon results from an inability of the electric field to efficiently pump energy into the system [23] because the electrons change their direction of motion due to the magnetic field. In Figure 1 we investigate this phenomenon for positrons in molecular hydrogen. We observe that the mean energy is a monotonically decreasing function of B/N for a fixed value of E/N. Since our calculations have been performed for zero gas temperature, we observe that the mean energy is much less than the thermal energy at 293 K in the limit of low E/N. The profiles of the mean energy reflect the energy dependence of the cross sections and are shifted towards higher values of E/N and lower mean energies for an increasing B/N. Similar behavior has been observed for positrons in molecular nitrogen and water vapour. This effect can also be investigated using the effective field concept (eq. 23 of [24]).

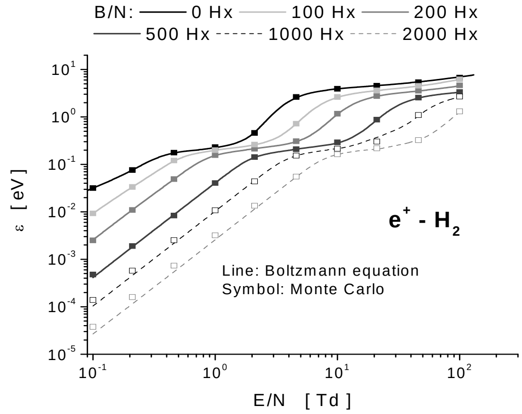

Figure 1: Variation of the mean energy of positrons in molecular hydrogen with E/N for various B/N.

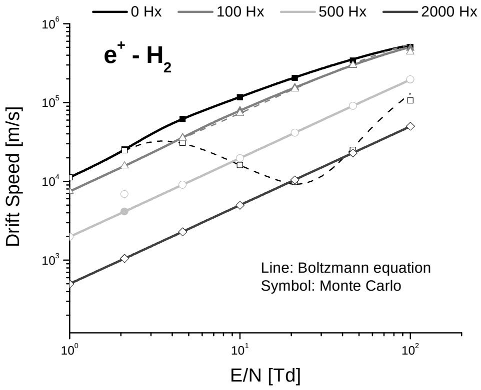

Figure 2: Variation of the drift speed of positrons in molecular hydrogen with E/N for various B/N. The flux values are represented by full lines and symbols, while the bulk values are given by dashed lines and open symbols.

2.2. *Is there NDC in* **E**×**B** *fields?*

As emphasized previously, when both the electric and magnetic fields are present, the drift velocity has two components: the longitudinal drift velocity component describes the drift along the electric field direction while the transverse component describes the drift along the **E**×**B** direction. Therefore, the drift can now be represented in terms of a drift speed and its direction is at some angle to the electric field (magnetic deflection angle). An interesting question arises: how does the magnetic field affect the drift speed under conditions when the cyclotron frequency is much less, of the same order, and much greater than the collision frequency? Figure 2 displays the flux and bulk components of the drift speed as a function of E/N for different values of B/N in these different regimes. We see that NDC effect has disappeared from the profiles for non-zero magnetic fields. For B/N of 100 Hx, a slight difference between the flux and bulk profiles still can be observed, but for the higher values of magnetic fields even this difference is absent. In order to understand the behavior of the drift speed it is essentially important to examine the longitudinal and transverse components of the drift velocity separately, as they exhibit completely different behavior in the presence of a magnetic field. In the profiles of $w_{\mathbf{E}\times\mathbf{B}}$ component there is a slight difference between the flux and bulk values but only for low magnetic fields, and this difference is in favor of bulk component. It is interesting to note that in the electron transport the difference between the flux and bulk components of $w_{\mathbf{E}\times\mathbf{B}}$ has never been observed. On the other hand, the profiles of the longitudinal component are lowered and shifted to the right compared to magnetic field free case. So, one could ask why has the NDC disappeared from the profiles of the drift speed in the presence of magnetic field? In the energy region where NDC exists for magnetic field free case, for the non-zero magnetic field profiles, the behavior of the drift speed is dominated by the component along the **E**×**B** direction. This is clearly evident from the profiles of the magnetic deflection angle shown in Figure 3. For B/N of 100 Hx, the flux magnetic deflection angle stays around 45° for the whole range of E/N considered, while the bulk value goes to 90° in the energy region where the Ps formation channel is open. This is the unique situation where due to the nature of collisions the flux and bulk drift velocities differ not only in magnitude, but also in direction.

3. Conclusion

In this work we have calculated various transport properties of positrons in neutral gases in crossed electric and magnetic fields using a multi-term theory for solving the Boltzmann equation and Monte Carlo simulation technique. The results obtained with these two different techniques are in very good agreement. We hope that present results and the multitude of interesting kinetic phenomena, induced by the synergism of magnetic field and Ps-induced non-conservative collisions, can be a good motivation for a further development of positron swarm experiments.

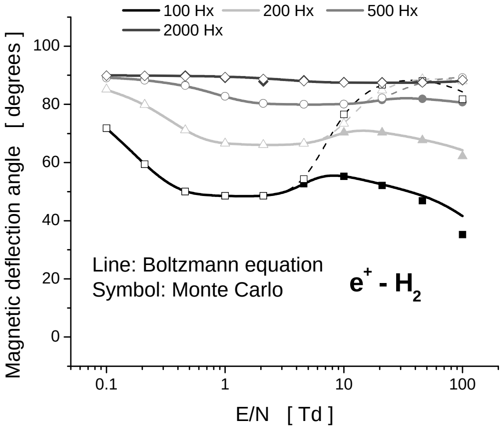

Figure 3: Variation of the magnetic deflection angle with E/N for various B/N. The flux values are represented by full lines and symbols while the bulk values are given by dashed lines and open symbols.

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