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Negative differential conductivity of positrons in gases

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ABSTRACT

This paper reports on a new series of calculations of positron transport properties based on current experimental cross section data. It is found that negative differential conductivity (NDC) occurs in the bulk drift velocity *W* but not the flux drift velocity *w*. The origin of the phenomenon lies in the "reactive" nature of positron collisions associated with positronium Ps formation, and is quite different in origin to the better known NDC effect in *w* arising from certain combinations of inelastic–elastic cross sections. Moreover, while the Ps formation process is qualitatively similar (at least from a kinetic theory perspective) to electron attachment, it is characterized by a cross section several orders of magnitude larger and hence the "reactive" NDC effect is correspondingly more pronounced. In this paper we test both established conditions for NDC, and develop new criteria, using simple mathematics and physical arguments where possible.

1. Introduction

Negative differential conductivity (NDC) can be defined as decrease of the drift velocity of charged particles (e.g. electrons, positrons) with increasing driving field. In general conductivity is a product of drift velocity and number density but changes in the number density are controlled by a number of phenomena mostly losses that are geometry dependent while the drift velocity itself is only controlled by the electron distribution function (EDF) and thereby is more fundamental and not a subject of particular properties of the system. Thus in fundamental studies the definition of NDC is confined to the dependence of the drift velocity on E/N only. In what follows we take a system of coordinates in which the z-axis is defined by the direction of the field $\boldsymbol{E}$.

NDC for electrons has been carefully investigated in the last two decades [1–4]. The reason for this is two-fold. On the one hand a number of applications are dependent on it while on the other it can cause undesirable instabilities. For example, the effect is important in gas discharges and for the operation of different kind of lasers. However, it also affects strongly the energy transferred to the plasma by Joule heating.

The conditions for NDC of electron swarms in gases summarized by Petrović et al. [1] and by Robson [3] are the following:

(1) Inelastic processes are necessary.
(2) NDC is favored by increasing momentum transfer cross section.
(3) Decreasing inelastic cross section favors NDC.
(4) Occurrence of NDC depends on relative magnitude of factors (2) and (3), with the precise criterion being given by Eq. (19) of Robson [3].
(5) Superelastic processes will have a tendency to reduce the NDC.

The drift velocity to which these conditions refer is the so-called flux drift velocity w which belongs to that family of transport coefficients defined through flux-gradient equations, in this case, Fick's law. It is also the spatially uniform average velocity, $w = \langle v_z \rangle$. The other type of drift velocity is the so-called bulk drift velocity, W, which belongs to that family of transport coefficients defined through the diffusion equation. It is the time derivative of the center-of-mass of the swarm, i.e. $W = d\langle z \rangle/dt$, where now the average is carried out over space. The two drift velocities differ whenever reactive, non-conservative (with respect to particle number) collisions occur, to a degree determined by the magnitude and energy-dependence of the reactive collision cross section. The difference is more than one of principle, for it is only W which is normally measured in experiments, not w.

Vrhovac and Petrović [4] have pointed out that there are some situations when bulk drift velocity may show NDC when flux drift

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velocity does not. This study was done specifically with electron attachment in mind, and NDC was found to occur only when flux drift velocity almost satisfies the criteria for NDC or at least a plateau in the drift velocity dependence is observed. Given the much larger magnitude of Ps formation cross sections, and the renewed interest in positron behaviour in gases, these calculations now assume a far greater significance.

We have used our new Monte Carlo (MC) code to investigate the transport of positrons in gases, particularly in argon, molecular nitrogen and hydrogen [5–7]. Positrons interactions with atoms and molecules are fundamentally different from those of electrons [8]. The first obvious difference is the absence of the resonance for positrons in nitrogen [6] which leaves very small non-resonant vibrational excitation and also a smaller number of electronic states that may be excited by positron impact. Second, the Ps formation channel, a non-conservative process not present for electrons has a significant cross section for positrons. In fact it can be several orders of magnitude larger than those for the equivalent process of dissociative electron attachment for electrons. The nature of ionization is also different as for positrons it is not a non-conservative process. The most striking feature of our observations was that negative differential conductivity (NDC) is observed in the bulk drift velocity even when the flux drift velocity does not show any signs of NDC. It was shown that the bulk drift velocity NDC is result of the non-conservative nature of Ps formation [5]. Here we check how the manifestation of NDC in positron transport fares against the previously mentioned theoretical conditions for NDC [1,3,4] and use our current results as a guide for modifying those conditions.

2. Monte Carlo results

All drift velocities presented here were calculated by MC simulations, which also produced rates of processes, particularly rates of Ps formation. Data for argon and nitrogen were presented earlier [5,6] while data for hydrogen will be presented later. First, we analyze whether the standard formula defining the difference between the bulk and flux properties [9] works well in this case. The formula is:

$$W = w - \frac{2\varepsilon}{3e}\frac{d\nu_{PF}}{dE}, \tag{1}$$

where ν_{PF} is the positronium formation rate, ε is the mean energy, e is the elementary charge and E is the electric field. We start from the MC flux drift velocity and add to it the second term from this equation where we apply the MC determined rates of Ps formation. The comparisons are presented in Fig. 1.

As can be seen, we obtained a qualitatively good agreement. The best is, of course, for N_2 but that is where the perturbation of the swarm by Ps formation is the weakest.

The next thing to investigate is if our calculated drift velocities satisfies the NDC criteria developed by Vrhovac and Petrović [4] which was the first to consider NDC due to reactive collisions. In the case of positrons the Ps formation takes the role of attachment. The criterion is given as

$$\frac{dW}{dE} = \frac{dw}{dE} - \frac{1}{e}\frac{2}{3}\left[\frac{d\varepsilon}{dE}\frac{d\nu_{PF}}{dE} + \varepsilon\frac{d^2\nu_{PF}}{dE^2}\right] < 0. \tag{2}$$

The region where the drift velocity falls and the predictions of the criterion coincide. The agreement is better for the onset than for the end of the range but overall the qualitatively prediction is good. It is worth checking whether conditions match those from Petrović et al. [1] or from Vrhovac and Petrović [4]:

$$1 + \frac{\frac{2}{3}\varepsilon\nu_1^{(PF)}}{\nu_{el}} + \varepsilon\frac{d}{d\varepsilon}\left[\frac{\frac{2}{3}\varepsilon\nu_1^{(PF)}}{\nu_{el}}\right] < 0. \tag{3}$$

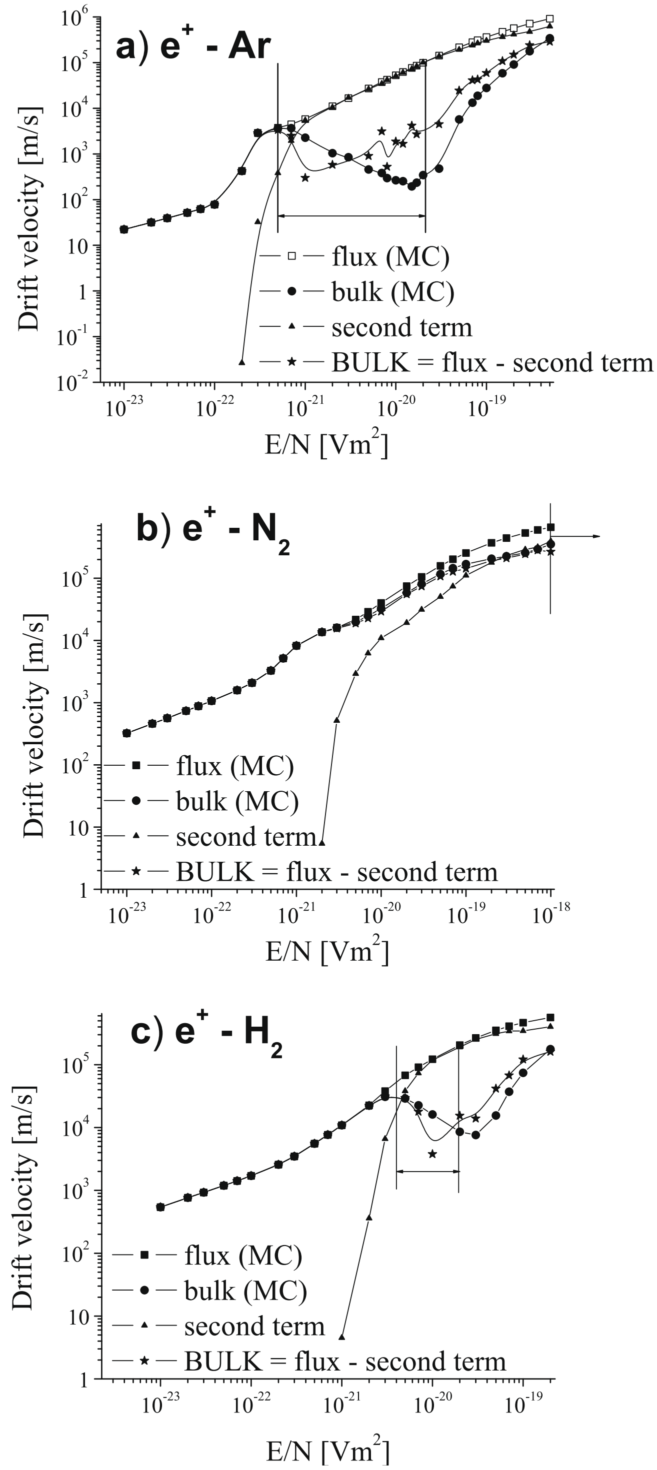

Fig. 1. Comparison between bulk drift velocities calculated using our MC code and predicted by Eq. (1) for positron transport in pure (a) argon [5], (b) nitrogen [6] and (c) hydrogen [7]. The calculations of the bulk drift velocity W were made both directly from MC and by modifying the results of Eq. (1) with calculated Ps formation rates. We also show as vertical lines the ranges of NDC predicted on the basis of the condition given by the Eq. (2).

Both for the flux drift velocity give any prediction of NDC, and in all cases there is no NDC according to these formulae. In Eq. (3) ν_{el} is the rate for elastic collisions while $\nu_1^{(PF)}$ represents the first derivative of the rate for Ps formation with respect to the mean energy. The NDC effect for positron is only for the bulk drift velocity when flux drift velocity is far from satisfying the condition.