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On new developments in the physics of positron swarms

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Abstract. Recently a new wave of swarm studies of positrons was initiated based on more complete scattering cross section sets. Initially some interesting and new physics was discovered, most importantly negative differential conductivity (NDC) that occurs only for the bulk drift velocity while it does not exist for the flux property. However the ultimate goal was to develop tools to model positron transport in realistic applications and the work that is progressing along these lines is reviewed here. It includes studies of positron transport in molecular gases, thermalization in generic swarm situations and in realistic gas filled traps and transport of positrons in crossed electric and magnetic fields. Finally we have extended the same technique of simulation (Monte Carlo) to studies of thermalization of positronium molecule. In addition, recently published first steps towards including effects of dense media on positron transport are summarized here.

1. Introduction

Over the past 3 years the field of positron swarms has been revitalized. The basis for the new series of papers was the recently measured cross sections for binary collisions [1-5] supported by equally sophisticated calculations [6,7]. The early studies of positron swarms produced a limited range of data due to technical difficulties in performing experiments and limited apparatus developed to treat non-conservative transport [8,9]. Thus we have only drift velocities for several gases [10,11] H_2, CO_2 and O_2. Drift velocities (W) for hydrogen were obtained at elevated *E/N* and show a surprising display of negative differential conductivity (NDC) which was explained [8] as being the result of mean energy dependent effective *Z* as the observable in the experiment is *W/Z*. It was uncertain whether other gases displayed NDC since the range of *E/N* covered did not extend sufficiently towards higher mean energies. It must be noted that theoretical-numerical calculations of transport coefficients for positrons were not performed at that stage as data for the cross sections were lacking and the experimental database was narrow and perhaps did not carry over to rare gases which would be easier to study. However, related to swarm studies and perhaps even belonging to swarm studies were the calculations and measurements of thermalization times and lifetimes of positrons in gases [12-14] which were performed continuously in spite of the demise of the other swarm studies.

Associated with swarm studies are the developments of gas filled positron traps [9,15] where collisions are used to thermalize positrons below the onset of Ps formation and even further down to energies below 100 meV. While those systems may not be viewed as primarily ‘swarm’ like systems, the basic description of the collisions and how a thermalized ensemble is formed can be described by swarm physics and phenomenology. In this paper we show results obtained by a Monte Carlo simulation with complete sets of cross sections for the low energy (below 20 eV) range as described in [16-18].

2. Recent results on swarms of positrons

The new series of papers on transport of positrons in gases has been primarily focused on revealing the transport properties under the influence of excessive non-conservative (number changing) processes. Positronium formation is at least two orders of magnitude larger than electron attachment and it has a sharp rise after the threshold. The most important result was the observation of very large negative differential conductivity (NDC) which occurs only for the bulk drift velocity.

There are two kinds of transport coefficients: the first, flux, which enter through the flux-gradient relation and the second, bulk, which are to be used in the diffusion equation. The difference between the two sets arises only due to energy-dependent number-changing processes such as attachment and ionization for electrons and Ps formation for positrons. The relationship between the flux and bulk drift velocities may be calculated from the rate of the non-conservative process (in this case ν_{PF} the Ps formation rate) [15]:

$$W_B = W_F - \frac{2\varepsilon}{3e}\frac{d\nu_{PF}}{dE}$$

In case of the NDC that was found for positrons [16,17], the special and unusual features were that (i) no NDC was present or even likely for the flux property, (ii) the difference between flux and bulk properties were as large as two orders of magnitude and (iii) it did not involve energy controlling processes, such as inelastic cross sections. The effect on the drift velocity and a similar effect for diffusion are caused only by the nature of the Ps formation. If there are inelastic processes in competition with Ps formation, such as in the case of nitrogen, the NDC practically disappears [18]. Nothing similar to this has been found for electrons but a general prediction of the effect was made [19] and it was found that for electrons this effect was not likely to occur.

In this paper we give a brief review of the more recent developments in the physics of positron swarms.

3. Positrons in liquids

The most interesting new development is the theory for the representation of charged particle transport in liquids [20]. This involved adjusting the magnitude and the shape of the cross section to account for coherent scattering off correlated particles. While this approach is valid only for non-polar molecules and includes only one of several possible effects occurring at high pressures this is a major first step and it revealed some of the important aspects of the physics that is involved. For example, as expected by the dependence of the de Broglie wavelength on particle energy the effect is pronounced at low energies, well below the threshold for Ps formation. The momentum transfer cross sections at energies up to a few eV are reduced considerably, leading to higher drift velocity in the liquid phase as compared with the gas phase [20] as well as other interesting effects for flux diffusion coefficients as shown in Figure 1. For drift velocity another form of NDC is induced purely by the structure of the medium, and its onset is well below the onset for the NDC caused by Ps formation and its non-conservative nature.

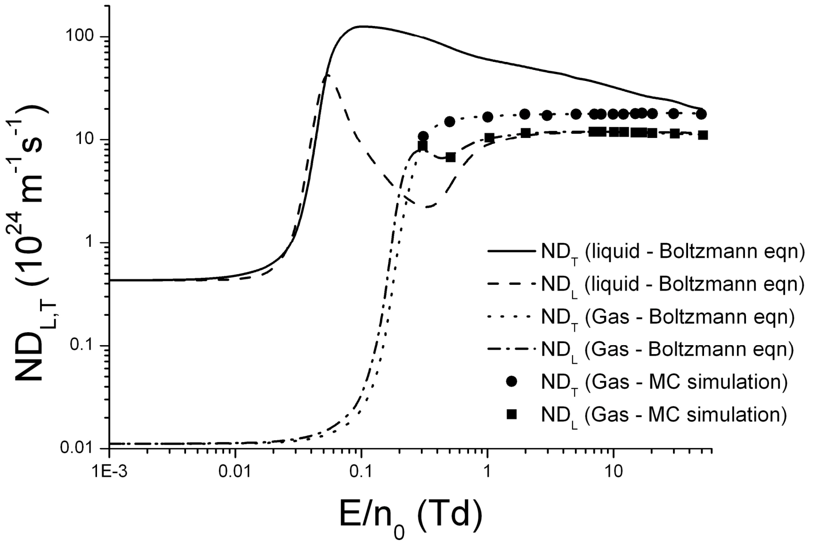

Figure 1. Diffusion coefficients for positrons in liquid argon calculated on the basis of cross sections given in [20] for liquid and [16] for gas phase.

It is essential to include other possible effects that may occur at high pressures and also to extend the theory to polar molecules, and these are the subject of current investigation. However, it is clear that at higher energies positrons move through a liquid in the same way as in a rarefied gas.

4. Positrons in crossed electric and magnetic fields

Most applications of positrons involve presence of high magnetic fields. In some cases the ability to tune independently the electric and magnetic fields may provide the desired degree of control over the properties of the ensemble. In any case even the first studies of transport (still unpublished but preliminary results were presented in [17]) have shown very interesting physical phenomena unlike any observed for electrons. The NDC in argon for example means that the bulk drift velocity (the drift velocity that includes the term due to non-conservative processes, is measured in actual experiments and is to be used in diffusion equation) may become very small, even two orders of magnitude smaller than the flux property (the property that is obtained by averages over velocity distribution and is to be used in flux gradient relation). At the same time there is an additional component of drift velocity when magnetic fields are present in the *ExB* direction. Unlike the *E* component, the *ExB* component of the drift velocity does not show a difference between flux and bulk properties (as there is no spatial segregation of particles along the *ExB* direction according to the energy). In the absence of NDC the *ExB* component is smaller than the *E* component. In the presence of NDC however, W_E may become very small and the overall W is dominated by W_{ExB}. Thus the total drift velocity W may not show NDC. Nevertheless it still has a strong mark of the non-conservative nature of Ps formation. The bulk drift velocity will be practically at right angles to the electric field (equal to the *ExB* component) while the flux property in the absence of NDC will be dominated by the *E* component. Thus the deflection angle between effective bulk and flux drift velocities will be quite large and instead of NDC the bulk drift velocity in magnetic fields has an additional deflection. The effect is shown for magnetic deflection in hydrogen in Figure 2. At very high magnetic fields normalized by the gas number density (in units of Huxley; 1 $Hx=10^{-27}$ Tm^3) the effect is reduced since deflection for the flux property is close to the right angle anyway so the non- conservative effect cannot change the direction very much [22]. The effect is also reduced at any effective magnetic field for nitrogen, which does not have the NDC [18, 21].

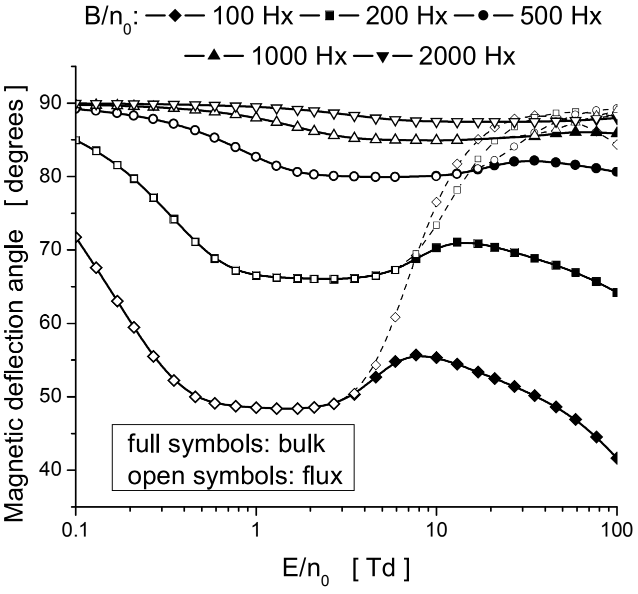

Figure 2. Variation of the bulk and flux values of the magnetic deflection angle for positrons in H_2 as a function of B/n_0 and E/n_0 in the crossed field configuration [21].

5. Thermalization of positrons and positronium in gases and in gas filled traps

One of the goals of the whole program is to model how positrons are thermalized and confined in gas filled traps. For an unbounded gas applying the primary sets of cross sections yields excellent agreement with experimental data for thermalization times [22].

Simulations for realistic geometry and other properties of a two stage Surko trap have been performed by the same technique. The conditions are: Stage I - N_2 $p=10^{-3}$ torr L=100 cm; Stage II – ($90\%N_2+10\%CF_4$) $p=10^{-4}$ torr L=100 cm; Barrier - 2eV; B=100 gauss; r=10cm – no losses on walls $T_{gas}=300K$; 2000 initial particles; initial beam energy 10eV directed (+/- 1eV transverse). The results shown in Figure 3a present the decay of the mean energy and in Figure 3b the decay of the number of particles. A 2 eV barrier in the backward direction is imposed between the two stages. The mean energy in the first stage is reduced to energies of the order of 2-3 eV. This, relatively high value of mean energies in the first stage, after 10 micro seconds, is maintained by the high energy particles returning from the second stage through the 2 eV barrier. In the second stage, thanks to efficient vibrational energy losses, mean energies are reduced down to the thermal value (Figure 3a). The number of particles (Figure 3b) drops down very rapidly and the local peaks represent transfers of the ensemble between the two stages. Overall the number is reduced to 50% of the initial number of positrons. One should be warned, however, that we have not included annihilation in our set of data. This is justified for calculation of transport coefficients as the number of such collisions is very small and in the MC procedure may not occur at all or so rarely that their statistics is very poor. On the other hand when energies fall below the threshold for Ps formation, annihilation is the only loss process and over extended time periods (such as times of the order of 1 s as covered here) annihilation may contribute as much as Ps formation to the losses and needs to be included for realistic calculations of the efficiency of trapping [23]. This technique enables us to modify the procedure applied to the trap in order to optimize its performance, for example by adding radial rotating electric fields [24].

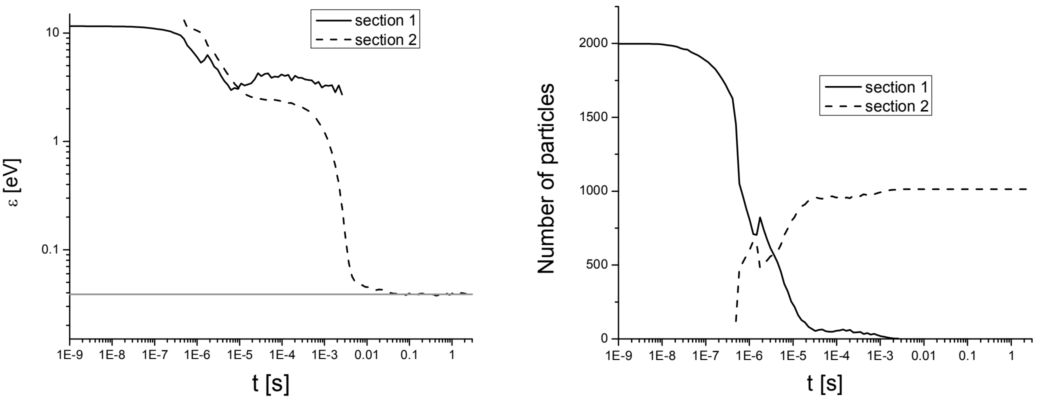

Figure 3. Temporal variation of the mean energy (a) and number (b) of positrons in a two stage Surko trap (conditions given in the text) [23].

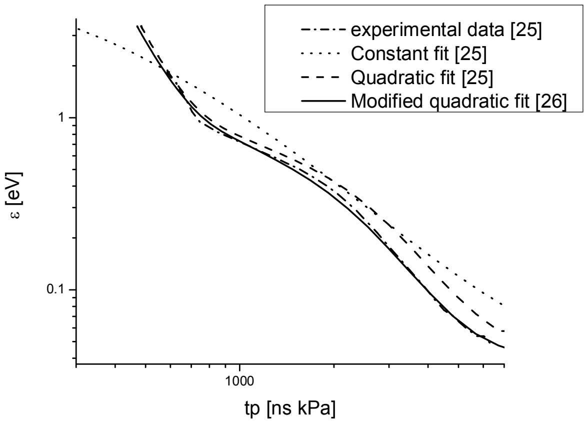

Figure 4. Thermalization of positronium (Ps) for different cross sections: dash-dot curve –experiment [25], solid black- modified quadratic fit [26], dotted and dashed-approximate theory [25].

Finally we mention the preliminary results on thermalization of Ps in He and water vapour. The experimental data were obtained in [25] and cross sections were derived based on approximate theory that assumes Maxwell Boltzmann distribution functions during the development of the Ps swarm. We have, on the other hand performed MC simulations and found that the distribution functions depart from a Maxwell Boltzmann distribution very rapidly due to selective removal of Ps in energy dependent cross sections [26]. Nevertheless the predicted thermalization (Figure 4) is still close to the experimental data requiring only small modifications of the cross section. Coupling of the codes for positrons and Ps would enable us to obtain the spatial profiles of the emitted gamma rays, which would be useful for the simulation of positron emission tomography (PET).

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