Applied Radiation and Isotopes 83 (2014) 148–154

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

On the use of Monte Carlo simulations to model transport of positrons in gases and liquids

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HIGHLIGHTS

- We analyze the application of Monte Carlo method for electrons in collisional plasmas.
- We try to implement the same technique for positron diagnostics and therapy.
- We explain how completeness of cross section sets is tested against swarm experiments.
- We propose use of averaged properties of the positron swarm for benchmarks.
- We present some new results for range, energy deposition and simulated tracks.

ARTICLE INFO

Available online 16 January 2013

Keywords:
Positrons
Monte Carlo simulations
Benchmarks
Radiation damage

ABSTRACT

In this paper we make a parallel between the swarm method in physics of ionized gases and modeling of positrons in radiation therapy and diagnostics. The basic idea is to take advantage of the experience gained in the past with electron swarms and to use it in establishing procedures of modeling positron diagnostics and therapy based on the well-established experimental binary collision data. In doing so we discuss the application of Monte Carlo technique for positrons in the same manner as used previously for electron swarms, we discuss the role of complete cross section sets (complete in terms of number, momentum and energy balance and tested against measured swarm parameters), we discuss the role of benchmarks and how to choose benchmarks for electrons that may perhaps be a subject to experimental verification. Finally we show some samples of positron trajectories together with secondary electrons that were established solely on the basis of accurate binary cross sections and also how those may be used in modeling of both gas filled traps and living organisms.

1. Introduction

The study of charged particle swarms in gaseous and liquid media under the influence of varying configurations of electric and magnetic fields is a topic of considerable interest both as a problem in basic physics and for its potential for application to modern technology. An understanding of collisional and transport processes for electron and ion swarms in gases is the basis for modeling of collisional plasmas (Makabe and Petrovic, 2006; Liebermann and Lichtenberg, 1994), high-energy particle detectors (Blum and Rolandi, 1993) and numerous other applications. On the other hand the knowledge of low-energy positron transport in gases under the influence of electric and magnetic fields has been used for explanation of the pertinent processes and optimization of positron traps (Marler and Surko, 2005; Marjanović et al., 2011). While gas filled traps are a worthy target for scientific interest the ultimate goal of such studies is in modeling of behavior of high-energy positrons in soft biological matter, or in other words for detailed quantitative representation of medical diagnostic procedures, such as positron emission tomography (PET) (Cherry et al., 2003; White and Robson, 2009). So far such studies were based on a number of semi-empirical and approximate representations of elementary physical processes which are difficult to extend to different circumstances and to generalize.

In this paper we shall first summarize the role of swarms in the physics of ionized gases. Measurements of transport data for electrons are directly used in plasma models but one can also fit

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0969-8043/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apradiso.2013.01.010

the experimental results and calculations by adjusting the cross sections. This procedure leads to the so-called swarm-derived cross section sets which provide a good prediction of the electron energy distribution function. At the same time it enforces good energy, momentum and number balances in the energy range covered by the swarm data. The transport theory developed for the swarms of charged particles in external fields is the fundamental basis of the theory of non-equilibrium collisional plasmas. Thus, calculating the transport data provides the best benchmark of a theory used in plasma modeling and especially its treatment of collisions. Measurements of the ionization and attachment rates, drift velocities, diffusion coefficients and characteristic energies proved to be the best way to test and sometimes even obtain the cross section sets and at the same time to give a theoretical basis to the plasma models (Makabe and Petrovic, 2006; Liebermann and Lichtenberg, 1994; Petrovic et al., 2009).

In this paper we discuss parallels between theories of ionized gases for electrons, electron swarms and models of radiation therapy-diagnostics by positrons and electrons. We try to pinpoint how similar procedures may be used and what should be the basis of such models and of their testing (benchmarks). Finally we present examples of trajectories and averaged properties (that may be used for benchmarking) and definition of test experiments. These calculations are solely based on quantities obtained from directly measured binary collision experiments and do not implement any averaged or semi-empirical quantities.

So what is meant by the term *swarm*? A swarm of charged particles is usually defined to be a group of such particles of density sufficiently low that both the charged particle–charged particle interactions and the influence of the swarm on the background molecule gas can be neglected. The behavior of the charged-particle swarms is therefore determined only through binary collisions with neutral molecules and by the forces exerted by the applied electric and magnetic fields. The collision times between the charged particles of the swarm and neutral molecules are assumed to be negligible in comparison with mean free time between collisions. As a consequence, all quantum-mechanical effects between collisions can be ignored and the motion of a swarm of charged-particles can be described with the laws of classical physics. This condition may not be met at high densities-pressures and in liquids where the wavelengths of particles may become comparable to the mean spacing between molecules. These issues have been dealt with in a separate series of papers (White and Robson, 2009, 2011; White et al., 2010, in this issue; Boyle et al., 2012).

If the key requirements are met and carefully controlled in swarm experiments then measurements of swarm transport coefficients can be unfolded to yield information about specific cross sections for charged particle scattering from neutral atoms or molecules (Phelps, 1968; Huxley and Crompton, 1974; Crompton, 1994). In addition to other well-established techniques, such as crossed-beam or total attenuation experiments, the swarm method was accepted as an efficient and complementary method of deriving the cross sections, particularly in the low energy range where other techniques were faced with a wide range of systematic problems. The swarm method has actually provided the most accurate information about low-energy electron–atom/molecule cross section (Petrović et al., 2007, 2009). Some of these information are still used as a tool for calibration and benchmarking other techniques of measurement and theory.

In the context of plasma modeling, however, swarms continue to play an important role through the provision of benchmarks for fluid and kinetic models of low-temperature plasmas in the free diffusion limit (Petrović et al., 2009). Transport coefficients of charged particle swarms are often directly used as an input for global (zero dimensional) and fluid models of gas discharges or as a means of evaluating the momentum and energy transfers in the fluid equations.

A number of theoretical methods to treat the problem of charged particle swarms have been developed, e.g., the fluid equation treatment (Mason and McDaniel, 1988; Robson, 2006; White et al., 2009; Robson et al., 2005), the Monte Carlo method (Raspopović et al., 1999; Petrović et al., 2002; Dujko et al., 2005), or the direct numerical solution of the Boltzmann equation (White et al., 2002, 2009; Robson and Ness, 1986; Ness and Robson, 1986; Dujko et al., 2010). Recent applications of these techniques to model transport of positrons in gases (Šuvakov et al., 2008; Banković et al., 2008, 2011, 2012a, 2012b, 2012c; Marler et al., 2009) and soft-condensed matter (White and Robson, 2009, 2011; White et al., 2010; Boyle et al., 2012) with the goal of optimizing positron traps and positron emission tomography is a clear sign of knowledge transfer from plasma and swarm communities to the positron community. The process of utilization and implementation of these techniques (as used in physics of gas discharges and collisional plasmas) in the field of positron physics has been triggered in the mid 2000s by research groups from the Institute of Physics in Belgrade (Serbia) and the Centre for Antimatter-matter Studies from Canberra and Townsville (Australia). This process is still active and the underlying assumption that there is a potential for increased collaboration between plasma physicists and those who work in the field of positron physics is also highlighted in much of the current innovation literature (Petrović et al., 2010, 2011; Sullivan et al., 2009).

At the same time the community dealing with radiation therapy has developed a number of very complex codes such as GEANT (Agostinelli et al., 2003) representing very sophisticated models of targets. While those have been used for most particles, applications for positrons are rare, and seem not to be of daily use in medical practice. The backbone of such models are Monte Carlo simulations of the motion of particles in the tissue model, which is often represented like a very dense gas. Such models often involve averaged properties (such as energy loss functions) or semi-empirical models, or if cross sections are implemented then simplified theoretical models are used, such as the Born approximation. Invariably these models do not analyze the transport in external fields so very simple implementation of the particle trajectories is sufficient. On the other hand representation of collisions still requires tests and possible benchmarking.

The two approaches seem to be converging whereas the former, in addition allows modeling of gas-filled traps as a full representation of the appropriate fields is available. We thus feel that it is an appropriate time where the same cross sections sets may be used to test the results and allow development of experiments to provide quantitative data for determining the cross section sets. We shall discuss how to make comparisons and how to shift the basis of modeling to the well-established binary collision data.

2. Monte Carlo simulations

The plasma and swarm communities have accumulated much practical experience over the years in the implementation of fluid, kinetic and Monte Carlo techniques in various spatial regions of non-equilibrium plasmas. The kinetic theory of charged particles is currently at such a level of sophistication that there is no need for phenomenological and approximate description of positron swarms. Theoretical methods and associated numerical codes for solving the Boltzmann equation initially developed for electron and ion swarms may be directly used for positron swarms. For

example, the collision operator for positronium (Ps) formation has the same mathematical form as the attachment operator for electrons within the multi-term framework for solving the Boltzmann equation. In the context of Monte Carlo simulations, we found that numerical schemes for a correct treatment of the electron attachment are fast, accurate and generally appropriate for Ps formation.

Monte Carlo simulations (MCS) proved to be the most flexible approach to modeling of charged particles in gases allowing exact treatment of boundary conditions and surface processes even based on experimental information and not involving mathematical boundary conditions. MCS also gave foundation to hybrid theories and particle in cell techniques for real plasmas especially for the non-local processes. At the same time MCS proved to be sufficiently fast providing an option to fit the transport data to obtain the cross sections by the swarm technique.

The Monte Carlo technique developed for electron swarms follows the motion of each particle between collisions allowing proper calculations of the effects of external electric and magnetic fields on the charged particle. Trajectory is determined by adhering to classical physics. In other words we assume that quantum effects, taking place during collisions, happen over a very short time compared to the mean time between collisions. The energy dependence of the cross sections make it difficult to determine the time to the next collision but modern computers even allow direct integration. The time to the next collision is determined based on a random number and is thus random in nature but the distribution is defined by the cross sections. Other random numbers define the type of collision, the energy loss and the scattering angle (using also the differential cross section as an input if necessary). All collisions are followed step by step. Averages are made following complex procedures defined by the nature of the transport coefficients, experiments and non-conservative nature of the collisions. Ionization and attachment require special scrutiny both in controlling the number of particles and in the definition of the experiment. All newly generated particles are followed to the end of their transport. The most complex part of the simulations is the definitions and implementation of the sampling routines for the transport coefficients. We have implemented codes that follow a large number of electrons in parallel and also that follow electrons one by one. Typically our codes achieve a statistical uncertainty of less than 0.1% with 100,000 to 1,000,000 electrons followed through many tens or hundreds of thousands of collisions. A more detailed description of the code and procedure may be found in our publications (Petrović et al., 2009; Raspopović et al., 1999; Dujko et al., 2005).

When it comes to the modeling of positrons in gases the same codes may be used to describe the physics of gas filled traps such as the Penning–Malmberg–Surko trap (Surko et al., 1989; Sullivan et al., 2008). The basic phenomenology often used to explain their operation was that of monoenergetic beams but MCS results clearly showed development of a broad swarm distribution and its development through time (Marjanović et al., 2011). In such cases where space charge and positron–positron interaction can be neglected, the properties of the positron cloud can be accurately represented by a swarm of particles. Monte Carlo simulation (Marjanović et al., 2011) is especially suitable for simulating inhomogeneous, multi-stage potential and pressure conditions inside such traps. The thermalization of beams in the trap is similar to the Frank–Hertz experiment where the transition from a monoenergetic initial distribution to a wide non-equilibrium distribution associated with the local electric field occurs (Franck and Hertz, 1914) (see Fig. 1). We may also calculate the thermalization time, losses due to different processes including positronium (Ps) formation and rates of all processes. We have also shown that MCS may provide results predicting rotating wall compression in the single charged particle regime.

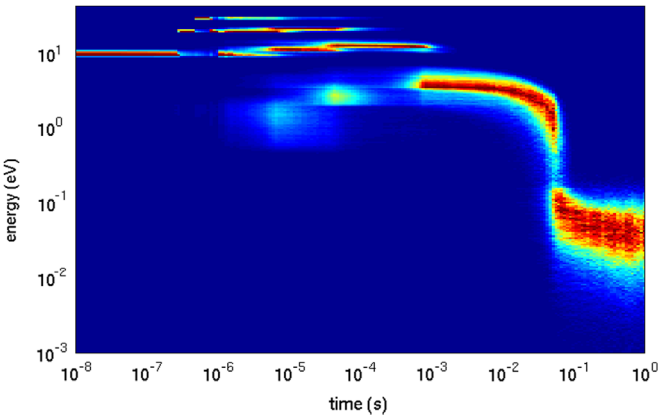

Fig. 1. Time evolution of positron energy distribution in a buffer gas filled Penning–Malmberg–Surko trap, showing the splitting of the initial beam into several distinct beams and evolution to a final thermal swarm.

The present example proves the following points. First one may object to the use of swarm based techniques as these are more complex by including external fields and, include a procedure which may be very difficult to follow, to determine the transport coefficients. The fields may be found in systems such as buffer gas traps but also the knowledge of the transport properties of electrons tells us that we may use all the knowledge accumulated for electrons to modify the positron energy distribution function. While external electric field may not penetrate the human body, the magnetic field will and may be used to control positrons. Second, we see that while the initial beam first breaks down into several beams, assuming monoenergetic particle distribution would be an inaccurate representation of the process and a broader swarm-like distribution is required, covering all from the non-local initial transport to a Maxwell–Boltzmann distribution function at the room temperature in the end.

3. Transport coefficients and cross section

The same experience with electrons allows one to interpret the calculated transport coefficients for positrons in gases, enabling the prediction of a number of kinetic phenomena such as negative differential conductivity (NDC) for the bulk drift velocity, which has not been observed for realistic systems with electrons. If these predictions prove to be a sufficient incentive for experimentalists to build experiments and measure the positron transport data, the swarm technique for the normalization of the cross sections would certainly be the main benefit.

In order to obtain the cross sections one needs good experimental transport data. While such data exist due to a number of high accuracy swarm experiments (Elford, 1972; Huxley and Crompton, 1974; Christophorou and Hunter, 1984) for positrons there were only a couple of attempts (Bose et al., 1981; Charlton and Laricchia, 1990). One cannot help but feel that in spite of formidable technical difficulties, the primary reason for the demise of such experiments could be the failure to understand the non-conservative transport at the time of the experiments. Such understanding exists now (Šuvakov et al., 2008; Marler et al., 2009; Banković et al., 2012b) and one could certainly take advantage of the data in a way that would ascertain the quality of the cross section sets.

Profiles of the mean energy, among many other interesting features, reflect the energy dependence of the cross sections. It

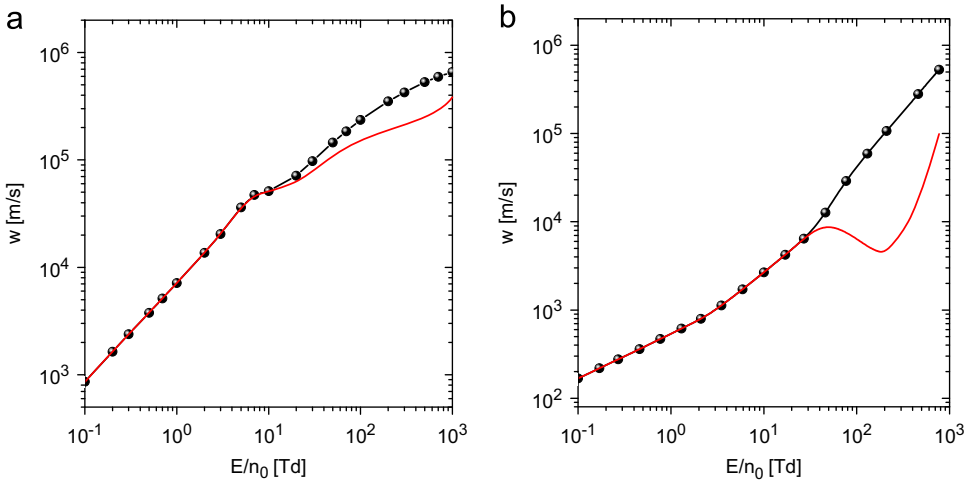

Fig. 2. Variation of the bulk and flux drift velocity components with E/n_0 (electric field intensity over number density of the background gas) in N_2–CF_4 (90–10) mixture (a) and in water vapor (b) (red line: bulk; black line and symbols: flux) (Banković et al., 2010b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

was shown that drift velocity profiles show a remarkable sensitivity to non-conservative Ps formation; the difference between the flux and bulk components exceeds in some cases more than two orders of magnitude. A very pronounced negative differential conductivity (NDC) is observed in the profiles of the bulk drift velocity component for positrons in Ar, H_2 and H_2O (Šuvakov et al., 2008; Marler et al., 2009; Banković et al., 2009, 2012a, 2012b). The NDC effect has been observed in electron transport as well (Petrović et al., 1984; Robson, 1984; Vrhovac and Petrović, 1996), but the nature of this phenomenon in positron transport is essentially different. In Fig. 2 we compare the drift velocities in a mixture of nitrogen and CF_4 (a standard cooling gas in traps) where no NDC is observed and in water vapor where bulk drift velocity NDC is visible, making more than an order of magnitude difference between the two definitions of the drift velocity.

Comparison between the transport data for electrons and positrons (e.g. for electrons no such NDC for bulk drift velocity has been found so far) emphasizes that one *cannot* and should not use electron scattering data for positrons, except for some special processes.

4. Benchmarks for electrons

Before embarking on a discussion how to design benchmark models for positrons having in mind their potential applications in positron-based technologies, we briefly review the impact of the benchmark models that have been developed for charged particles within the swarm and plasma modeling communities. Since the late 1970s the number of MC simulations and solutions to the Boltzmann equation that are not limited in the number of expansion terms (as used for electron swarms), has been significantly increased. The limitations of the two-term approximation for solving the Boltzmann equation were illustrated by many groups, and one of the goals was to probe the limitation of the two-term approximation, and to serve as an independent check on the accuracy and reliability of the increasing number of multi-term Boltzmann equation solutions. The Reid-ramp model (Reid, 1979) has become the standard test for solutions of the Boltzmann equation (Penetrante et al., 1985; Brennan et al., 1990), particularly in the light of the known failure of the two-term approximation for this model. Ness (1994), White et al. (1997) and Raspopović et al. (1999) extended this model to the situation involving $\mathbf{E}\times\mathbf{B}$ fields. Their results validate both the hydrodynamic theory of Ness (1994) and the numerical accuracy of a Monte Carlo code used by Raspopović et al. (1999). Further extensions of this model include the work of White et al. (1999) where the model was extended into the domain of electric and magnetic fields crossed at arbitrary angle. The recent benchmarking of a multi-term theory for solving the Boltzmann equation for electron swarms in radio-frequency electric and magnetic fields deserves special mentioning: the Reid ramp model was used as a benchmark model and some paradoxical manifestation of the diffusion coefficients initially observed by a Monte Carlo method (Raspopović et al., 2000) was confirmed by independent analysis performed by a multi-term approach for solving the Boltzmann equation White et al., 2010. There are many similar examples in the literature, but the above are used as illustrative examples having in mind the complexity of phenomena, and the explicit contributions of the Belgrade and JCU (James Cook University) groups.

While the Reid ramp model is a benchmark model where only conservative interactions between the charged particle and background molecules take place, the ionization model of Lucas and Saelee (Nolan et al., 1997), and attachment models suggested by Ness and Robson (1986), were specifically developed to investigate the explicit and implicit effects of non-conservative collisions on various transport coefficients. The initially developed ionization models of Lucas and Saelee and attachment models of Ness and Robson have been recently extended to the domain of electric and magnetic fields crossed at arbitrary angles (Dujko et al., 2010). The extension has been also performed into the domain of radio-frequency electric and magnetic fields, where many atypical manifestations of the drift velocity and diffusion tensor were observed (Dujko and White, 2008).

5. Strategy for positron benchmark calculations: individual tracks or averages

Experience with benchmarks for electrons gives confidence for the solutions of general charged particle transport to arbitrarily high accuracy. Even better, some cross section sets for realistic gases could be used and tested against experiment. For example, tests for gases (such as CF_4 and others) in DC electric fields, and excellent consistency of different approaches for RF fields, extends our confidence from DC swarm experiments and provides

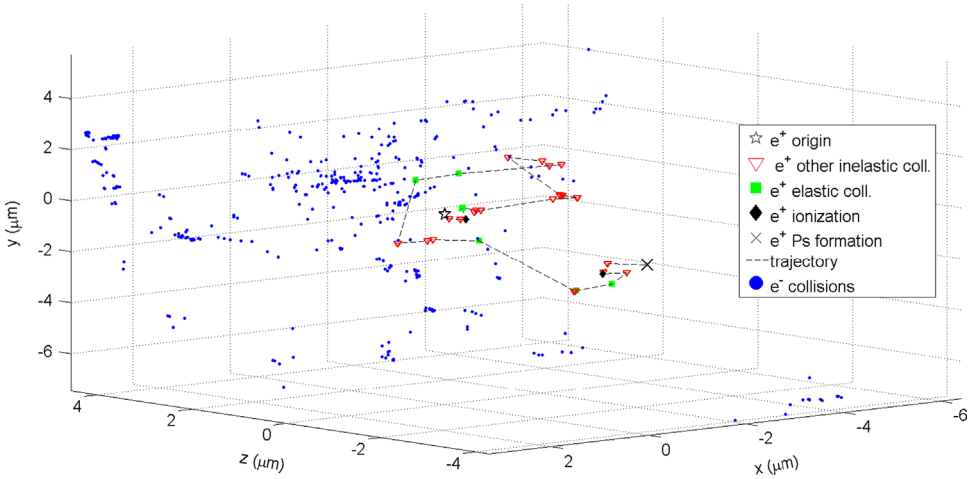

Fig. 3. Track of one positron through the water vapor environment at atmospheric pressure. Points of collision are presented for various processes for the positron, and also points of collisions for all of the secondary electrons (Marjanović et al., to be published). The point where Ps is formed is denoted by *X*.

motivation for the development of new swarm measurements using RF electric fields.

The standard (non-swarm) approach to event-by-event Monte Carlo simulations which is often relied on involves presenting the particle tracks (Garcia et al., 2011). One such example for water vapor (which can thus be regarded as a basic model of the human body) is shown in Fig. 3. It shows both the positron trajectory (starting at 1 keV) and the points of collisions of secondary electrons created in its wake. It is impossible to discern different trajectories if all of these are connected. Thus we show the points of collisions as an indication of the extended range and multitude of secondary electrons.

While the trajectory approach is visually a very detailed, and appealing representation, it does not provide a good basis for comparisons between different models of scattering, as individual trajectories within one model may vary more than the average (the most representative) trajectories of different models.

Based on experience from electrons we propose an alternate approach involving the use of averaged properties. One such property may be the properly defined range of particles. It is perhaps averaged with weak dependence on basic collision models, but it provides a good knowledge of momentum transfer collisions akin to the diffusion coefficient and, in addition, it may be measured. In Fig. 4 we show one such calculation for a simple scattering set for cross sections and isotropic scattering for water vapor. The range is calculated from the active positrons remaining in the system. At later times only very few positrons remain and at those times they are thermalized. The range of positrons (unlike electrons) cannot grow any further and it is actually smaller than the maximum which was achieved when more positrons were available. It also appears to be constant as the positrons are at room temperature moving very slowly and having a lot of collisions. Thus they cannot travel far from their ultimate positions. One should thus use the maximum range for positrons and not the later time constant value. We also show the range of the secondary electrons that are produced, which has the consequence of greatly extending the effect of the primary particles and may indicate the possibility of particle-induced damage in a significantly greater volume. Associated with this one could determine a diffusion coefficient which, however, would be much more difficult to measure if required. At this moment the transport of positronium is not included in the simulation, although we did a separate study of positronium transport based on the existing cross-section set for positronium–H_2O interaction.

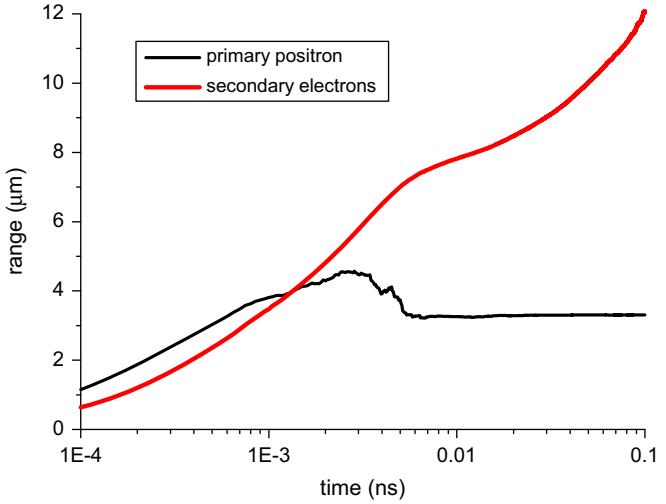

Fig. 4. Range of positrons in water vapor at atmospheric pressure. We also show the range of secondary electrons (Marjanović et al., to be published).

At every collision of a positron or electron with the background gas, we sample the energy that is transferred to the target H_2O molecule. This energy is considered to be deposited in the medium. We also sample the distance of these collisions from the origin of positrons. In this way we obtain the spatial profile of the energy that is transferred to the medium. This information is vital to determining the dose that the patient receives during a treatment, and to determining the volume of the affected tissue. Deposition of energy and energy transfer (loss of energy in the volume) is thus another averaged property that may be used to represent the ensemble and provide a benchmark. The result for water vapor is shown in Fig. 5. Finally a standard, averaged value that is often measured is the thermalization time and calculations based on elementary collision data have proved to give excellent agreement with the existing experimental results (Banković, 2012).

6. Modeling of positron transport through human tissue

Another venue of research that lends itself to the swarm approach is the modeling of positron transport through living human tissue. Understanding the processes that positrons initiate at high energies, as well as low energies, is important for determining the accurate dose that a patient receives during a

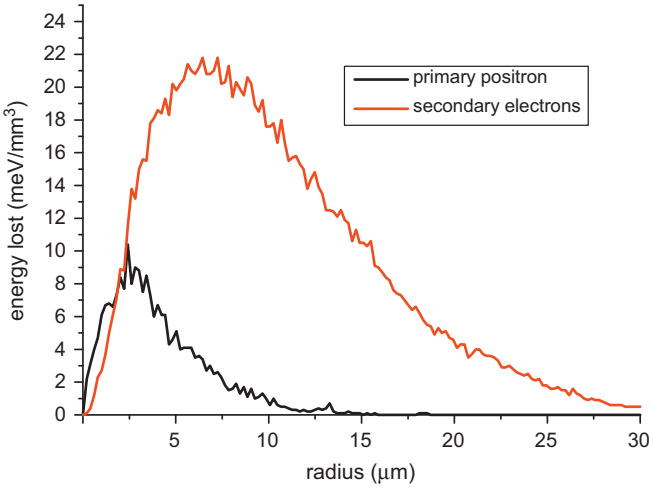

Fig. 5. Energy deposited in the medium in a spherical shell of radius *r* and thickness *dr* per one positron and its secondary electrons. The energy released after the positronium formation process is not taken into account. Most of the positrons energy goes to secondary electrons in the process of ionization (Marjanović et al., to be published).

PET scan or positron radiation therapy. At the initial stage of research, the best supplement for human tissue is dense H_2O vapor and later, the same approach can be extended to modeling positron transport in liquid water.

Collisions of positrons (and electrons) in liquids may be represented as simultaneous collisions on several targets when the mean distance between molecules is smaller than the wavelength of the particle. Under those circumstances the complexity of coherent scattering and subsequent interference require using structure factors to modify the cross sections (White and Robson, 2009; White et al., 2010). It was shown that for energies above 5 eV, a liquid may be represented by binary collisions. For lower energies one, however, needs different cross sections for momentum and energy balances and the effects of the liquid may be considerable. We shall leave further discussion of the relevant issues to another paper in this volume (White et al., in this issue). These cross sections may however be employed in modeling of the human tissue which is well represented by the liquid water. Thus one could say that the results shown in Figs. 3–5 are relevant for the human body with a provision that the low energy section would be modified by the effect of the liquid on the scattering. Having in mind that the momentum transfer cross section in liquids is smaller than that for binary collisions the range of low energy particles would be somewhat extended (which would affect secondary electrons more than positrons). We believe that with development of experimental determination of the averaged properties it would be possible to test how well do we represent the liquids in the scattering models.

With the flexibility of our Monte Carlo code we are not only able to track a positron from its origin to the point of positronium formation, but also we can follow the resulting positronium until annihilation (Marjanovic et al., 2012), as well as all of the electrons that are produced by the positron through ionization of H_2O molecules. These tracks can be visualized like the example in Fig. 4. While a single track is good to visualize the processes and the shape of positron trajectories, it does not offer complete information about the impact that the treatment has on the patient. That is why a large number of positrons is simulated and properties of the entire swarm are sampled.

In the simulation, the positrons originate at one point in space. In order to obtain good statistics, several millions of particles are simulated. The tissue is represented by H_2O vapor at atmospheric pressure and room temperature. The positrons are initialized at high energies, in excess of 1 keV, and lose most of their energy through several ionization collisions with water molecules. At each ionization process an electron is introduced to the simulation at the point of collision where its resulting velocity is determined using the Opal–Peterson–Beaty formula (Opal et al., 1971) and obeying the laws of conservation of energy and momentum. These electrons are simulated further and some of them even have enough energy to produce additional electrons through subsequent ionizations. As the number of electrons can climb very high, this can significantly increase the computation time. Therefore once an electron thermalizes and its energy drops below 100 meV it can no longer significantly contribute to the tissue damage and is removed from the simulation in order to reduce computation time.

7. Conclusion

We have reviewed the implementation of MCS for electrons and positrons in gases, based on standard swarm techniques, as applied in the modeling of ionized gases. The parallel leads to a proposal of several averaged properties which may be used for quantitative comparisons and tests of positron scattering cross section sets.

In case of electrons it has been known for a long while that the transport properties may be used to unfold the cross sections, and even more importantly to test the completeness and applicability of cross section sets for modeling of low temperature plasmas. The same plan cannot be applied for positrons in gases as positron swarm experiments are lacking. At the same time plots of tracks, while full of information and a very good visual representation still cannot be used to compare different cross section sets or test the validity of codes. This is so since each track is significantly different from the others even for the same set of cross sections.

Thus we propose several averaged properties some of which may be even measured by experiments simpler than the standard swarm experiments applied to positrons. Those include standard properties like range, energy lost in collisions with the background gas and thermalization time. While not as well defined and not as precisely measured as electron swarm properties these quantities may offer the positron physics the same advantages as given to the non-equilibrium plasmas by electron swarm studies. The results presented in this paper are new calculations based on the best available cross sections for water vapor (Banković et al., 2012b). It is possible to separate the effects due to positrons and secondary electrons. It is also possible to observe that secondary electrons extend over a much larger area.

We also show a positron track in water vapor calculated solely by using the binary cross sections measured in experiments, or determined and tested. The averaged properties and associated benchmarks provide a basis to compared scattering models, test the codes, and compare different approaches stemming both from physics of ionized gases and also from radiation therapy. At the moment we may conclude that swarm based models are fully compatible with more complex models and geometrical representation of the targets may be used in the same way as the existing radiation therapy based codes. At the same time swarm based approach allows the use of the same approach for both analysis and normalization of the traps used for measurements, modeling of experiments and optimization of the procedure by modifying the magnetic field (and if possible the electric field).

Acknowledgments

This work was supported by the MNTR, Serbia, under Contracts ON171037, III41011 and SANU155.

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