Positron transport in gases

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Abstract. We review the field of positron transport physics in gases, starting with a historical overview. In particular, experiments which have measured positron drift velocities and mobilities in specially constructed cells are highlighted. The relevance of understanding positron transport in current efforts to manipulate trapped clouds of positrons is emphasised. We suggest some ways in which the output of a positron accumulator might be used to develop a new and versatile technique to study positron drift.

1. Introductory remarks and contemporary relevance

Before the advent of low energy, quasi-monoenergetic, positron beams, the only way to extract (experimental) information regarding positron collisions was to use systems in which the positrons emitted from a radioactive source stopped directly in the gas sample under study. Depending upon the target species, and other circumstances, the densities used were typically in the Amagat range (1 Amagat = 2.69 x 10^25 m^-3) to provide sufficient signal from the positrons stopping and annihilating in the gas, rather than the prompt “background” emanating from those positrons that reached the walls of the confining chamber. Data were usually extracted by monitoring positron annihilations in the gas; see e.g. [1] for a description of the techniques involved.

The kinetic energy of a positron emitted from a radioactive source into a dense gas is moderated into the eV-range within a short (sub-ns) period. The scattering processes involved in the slowing down (ionization and excitation of the gas) have cross sections typically many orders of magnitude larger than that for annihilation with an atomic or molecular electron, such that almost all of the positrons reach the energy range below the ionization energy, \( E_{\text{ion}} \), of the gas. Of most concern to us here will be those positrons whose energies fall below \( E_{\text{Ps}} = (E_{\text{ion}} - 6.8) \) eV, the so-called positronium formation threshold of the gas. Such positrons cannot capture an electron directly from the target gas to form positronium, the quasi-stable electron-positron bound state (with a ground state binding energy of 6.8 eV), and usually annihilate as so-called “free” positrons, following diffusion and/or drift in the gas.

Experimenters, often with theoretical support, were ingenious in extracting information with the limited techniques at their disposal. To mention just some areas of study: non-equilibrium effects apparent due to annihilation during the slowing down were analysed to extract positron thermalisation times, tests of scattering theory and to probe localisation phenomena at low temperatures; electric fields were applied to gases and the changes with respect to the zero-field case gave crude, but surprisingly accurate, estimates of the elastic scattering cross sections for some of the noble gases; attempts were made to measure positron drift velocities and mobilities in gases and radiation chemical
effects were brought into play to help extract similar information. Further details will be given in the following sections.

The main drawback of all of this work was the lack of control of the experimenter over individual collision events, including impact energy and selectivity of outcome. This had long been known, and the obstacles were finally begun to be overcome with the development of the low energy positron beam, mainly from the early 1970’s onwards. Gradually more became known about the details of positron interactions with gas atoms and molecules as total scattering cross sections, and partial cross sections for some channels, were measured with increased confidence and accuracy. Inevitably, interest in what might be termed positron-gas “swarm” techniques began to wane, and there are currently very few groups worldwide still with competence in this area.

Nevertheless, there is renewed interest in positron transport effects in gases. Modern theoretical techniques, which have been applied extensively with great success to electron transport (see this issue), are beginning to be applied to positrons [see e.g. 2-4]. This will perhaps herald a new era for positron transport work, with some qualitatively new phenomena to study [2]. Furthermore, the importance of positron interaction with gases and positron cooling and transport have been highlighted by recent advances in positron trapping and accumulation and their applications [see e.g. 5-8]. This will be discussed further below, since modern positron beam technology could play an important role in reviving interest in the positron transport field.

In the remainder of this article we will describe some of the phenomena involved in positron slowing and transport, including highlight results from the archive. We will briefly discuss the previous attempts to extract positron drift speeds using positron lifetime and related techniques, and describe why such experiments present formidable challenges (and hence why so few were done). Modern techniques which use positron transport will be introduced, with the aim of highlighting synergies with the resurgent theoretical interest in such phenomena. This will lead to a discussion of possible new opportunities and directions in the field.

2. Basic positron phenomenology

Our aim in this section is not to be comprehensive, but rather to highlight relevant aspects from the positron field. It seems logical to follow the positron as it loses its last few electron-Volts of kinetic energy, into equilibrium with its surroundings and interaction and annihilation. The treatment will be mainly experimental/empirical in nature, but reference will be given as appropriate to theoretical work. We start, though, with a brief description of a typical timing experiment.

2.1. The positron lifetime technique

In this method, individual events are collated into a lifetime spectrum by recording the time difference between the emission of a positron from a radioactive source and its subsequent annihilation in the gas. The former is usually done by registering the nuclear gamma-ray which accompanies the beta-decay of $^{22}\text{Na}$, whilst the annihilation gamma-ray provides the stop for the timing sequence. The gamma-rays are detected using a pair of scintillation counters arranged appropriately on the exterior of the chamber which contains the gas and the source. Standard timing electronics is used to record the lifetime spectra; see [1, 9, 10] for more details. Occasionally, a method in which the beta-particle was timed directly left the source, using a thin scintillator technique, has also been used [1, 9].

We are only concerned with the free positron component of the lifetime spectrum, to which we assign a time spectrum, $S_f(t)$. The instantaneous annihilation rate of the free positrons, $\lambda_d(t)$, is given by

$$\lambda_d(t) = \frac{S_f(t)}{\int_0^\infty S_f(t) \, dt} = \omega \rho Z_{\text{eff}}(t),$$

(1)

where $\omega \rho$ is the Dirac annihilation rate for a free electron gas with number density, $\rho$, and $Z_{\text{eff}}(t)$ is the time-dependent effective number of electrons available to the positron for annihilation per gas atom or
molecule. This parameter is related to the velocity, or energy dependent $Z_{\text{eff}}$, viz $Z_{\text{eff}}(E)$, given a time dependent positron energy distribution $f(E,t)$ as,

$$Z_{\text{eff}}(t) = \int_0^\infty Z_{\text{eff}}(E) f(E,t) dE \int_0^\infty f(E,t) dE.$$  

(2)

In equilibrium, $Z_{\text{eff}}$ is a constant, averaged over the energy distribution of the positrons, such that the measured annihilation rate is given by

$$\lambda_f = \omega \rho Z_{\text{eff}} = 0.201 \rho Z_{\text{eff}} \mu s^{-1},$$  

(3)

where the gas density is in units of Amagat. Thus, an equilibrium free positron lifetime spectrum will consist of a single exponential component, possibly preceded by a non-exponential region if the timescales for slowing down and annihilation are comparable. A classic example is the spectrum shown in figure 1 [9], which is for room temperature argon gas at a density of 6.3 Amagat. Note in particular curve (c) from figure 1 which displays the exponential decay at long times, but has a pronounced “shoulder” on approaching $t = 0$ as a result of annihilation whilst slowing down. Such behaviour is typical of the noble gases, and is particularly striking in argon, krypton and xenon where the variation of $Z_{\text{eff}}(E)$ leads to dramatic effects upon $Z_{\text{eff}}(t)$. The latter, computed from (1), is shown in figure 2 for the same gas and conditions as the example in figure 1.

![Figure 1. Positron lifetime spectrum for argon gas at room temperature and at a density of 6.3 Amagat. The spectrum is broken down into components, the most relevant for the present discussion being that for the free positrons. The effect of non-thermal annihilation (the shoulder) is evident at short times.](image-url)
2.2. Positron slowing down

The instantaneous $Z_{\text{eff}}$, $Z_{\text{eff}}(t)$, displayed in figure 2, can be characterised in terms of a shoulder width, $\tau_s$, which is related to the thermalisation time of the positrons. It is inversely proportional to gas density (such that values for $\tau_s\rho$ in ns-Amagat are usually quoted) and, following early work [11], can be defined using

$$Z_{\text{eff}}(\tau_s) = (Z_{\text{eff}} - 0.1\Delta Z), \quad (4)$$

where $\Delta Z = (Z_{\text{eff}} - Z_{\text{min}})$, as illustrated in figure 2.

The behavior of $Z_{\text{eff}}(t)$ across the shoulder region in the noble gases has, historically, been the subject of much investigation. Indeed, before the advent of positron beams analysis of this region was one of the only ways in which information regarding positron scattering cross sections could be derived. This included an intriguing study [12], comparing the shoulders for argon gas at room temperature and at a much lower temperature (~ 100 K), which deduced that the momentum transfer cross section possessed a Ramsauer minimum at low energies. This was later directly observed in the total scattering cross section using a low energy beam [13]. Overall, little has changed regarding theory-versus-experiment for positron-noble gas shoulders since the situation was last reviewed, and readers are referred to that literature [1, 10] and references therein. However, with an array of more accurate scattering cross sections becoming available, it may be worthwhile to revisit this topic.

It is more difficult to observe the effects of positron slowing down in pure molecular gases, where the presence of rotational and vibrational channels down to sub-eV energies usually means that timescales are sufficiently short that non-thermal effects are not directly visible in lifetime spectra. An exception is N$_2$, and this gas has been studied in detail [14]. This molecule is also important in positron accumulation physics, as will be described below.
Information on thermalisation times of positrons in molecular gases can be gleaned by studying the behaviour of the shoulder in argon gas upon controlled addition of small quantities of impurities, as was first shown by Paul and Leung [11]. The most recent study using that technique reported thermalisation times for a range of species [15], noting ultra-fast thermalisation in SF₆ for example. The importance of this observation will also be detailed below in connection with its use for cooling in positron accumulators.

The classic early discussion of positron slowing down in gases was that for argon given by Tao, Green and Celitans [16]. It is still worth reading this paper for the clarity of its treatment. A broadly similar approach was taken by Jacobsen [17] who computed estimates for the density-normalised thermalisation distance, \( R_\rho \), for positrons in various gases. The motivation here was to account for density-dependent positronium formation in dense molecular gases, in which combination of a positron with an electron created during its slowing down in the gas could occur. This will be discussed further in the next section.

Jacobsen [17] found an approximate, but convenient, expression for \( R_\rho \)

\[
R_\rho = 2 \times 10^5 (\tau_{sp}/\sigma)^{1/2} \text{ Å-Amagat},
\]

where \( \tau_{sp} \) is the density-normalised thermalisation time (in units of ns-Amagat), which could be taken from experiments such as those described above, and \( \sigma \) is an average low energy scattering cross section (in Å²). The difficulty lay in estimating a value for the latter, but using the same procedure to estimate thermalisation times in the noble gases he found agreement with experiment to around a factor of 2-3, which gave confidence that estimates based upon the slowing down model can be used as a reasonable guide. In principle, with accurate low energy (typically sub-eV) scattering and annihilation cross sections hopefully becoming available for a range of gases of interest, it should be possible to model accurately the approach to thermalisation and derive values for density-normalised time and length scales.

2.3. Electric fields, positronium and radiation spurts

From the early years of positron-gas physics, researchers have applied electric fields, \( \varepsilon \) (magnitude, \( \varepsilon \)) across their chambers in an effort to learn more about positron scattering. The first notable work was that of Marder et al. [18] who studied the behaviour of the fraction of positrons which formed positronium as \( \varepsilon \) was increased. In most cases they found that the fraction increased with field as the mean energy of the positrons became high enough for them to capture an atomic or molecular electron in collision to form positronium. In simple terms a charge, \( e \), and mass, \( m \), in a field \( \varepsilon \) will undergo an acceleration, \( a = e\varepsilon/m \) and hence the change in kinetic energy between collisions is

\[
m(v + at)^2/2 - mv^2/2 = e\varepsilon \cdot l + (e\varepsilon l)^2/2mv^2,
\]

where \( v \) is the velocity at the beginning of the free path of length, \( l \). The first term on the right hand side will sum to zero over many collisions, so that the positron gains on average a kinetic energy of \( (e\varepsilon l)^2/2mv^2 \) from the field. Equating this to the mean energy loss per (elastic) collision with an object of mass \( M \) of \( m^2v^2/M \) it can be seen that the positron kinetic energy will tend towards an equilibrium of the order of

\[
(M/8m)^{1/2}e\varepsilon = (M/8m)^{1/2}(\varepsilon/\rho)/\sigma \text{ (eV).}
\]

It is easy to see that this can be quite a substantial gain, with \( \sigma \approx 10^{-20} \text{ m}^2 \) and density-normalised fields \( (\varepsilon/\rho) \) around 1 Td (= 10⁻²¹ Vm⁻² ~ 270 Vcm⁻¹Amagat⁻¹). A detailed Boltzmann equation approach to derive elastic scattering cross sections for helium, neon and argon was developed by Teutsch and Hughes [19] in an accompanying paper to [18] (see also the discussion in [16]). The main result of
these investigations is that the positronium yield in the noble gases increases with electric field, typically to saturation. The situation is summarized in figure 3 for argon gas [20].

![Figure 3. Variation of the yield of positronium atoms (relative to zero field, left scale; absolute fraction, right scale) versus applied electric field for argon gas. The points marked present work are from [20], whilst Marder et al. is the work in [18].](image)

However, this situation does not always pertain with molecular gases. Even in the earliest studies on molecular gases an anomaly at a relatively low density of around 2 Amagat of SF$_6$ was found in which the positronium fraction was found to fall with field [18, 21], before rising as expected at higher fields [21]. Similar phenomena have been seen in a number of other gases [22-24] and other media [25, 26]. This is now understood in terms of the spur model of positronium formation [27, 28] in which positronium can be formed by a positron combining with an electron that it has created in one of its final ionizing collisions. The applied electric field tends to separate the positron and electron and will, at least at low fields, reduce the positronium yield.

At zero externally applied electric field a semi-quantitative model for the fraction of positrons forming positronium, $F$, [28] yields the expression,

$$F = F_o + (1 - F_o)\exp(-\lambda_f \tau_{Ps})[1 - \exp(-r_c/R)].$$  \hspace{1cm} (8)

Here $F_o$ is the positronium fraction at “zero” density (i.e. that formed directly in collision via the so-called Ore mechanism) and $R$ is the thermalisation distance discussed above. The second factor in (8) is the contribution from the positron spur, and is expected to be density and temperature dependent, and there have been several observations of such effects [1, 10, 29]. The parameter $r_c (= e^2/4\pi\varepsilon_0 kT)$ is the critical Onsager radius at which the potential energy of a charged pair in a medium of dielectric constant, $\varepsilon_0$, becomes equal to the thermal energy, $kT$. The factor $\exp(-\lambda_f \tau_{Ps})$ is the probability that the positron has not annihilated before the pair can recombine with a characteristic time, $\tau_{Ps}$, given by [28],

$$\tau_{Ps} = 4\pi\varepsilon_0 R^3/3e\mu_\star.$$  \hspace{1cm} (9)
with $\mu$, the positron mobility for the gas at a particular temperature and density. Thus, the importance of transport physics in positronium phenomena (via $R$ and $\mu$) should, at least qualitatively, be clear. Positronium formation via the spur mechanism is a ubiquitous phenomenon in, for instance, dense gases, liquids and molecular solids [27, 30]. Contemporary relevance may be the issue of positron transport leading to positronium formation in bio-materials, particularly of relevance to medicine.

3. Positron drift experiments
As mentioned in section 1, there have been attempts, albeit very limited in number and scope, to directly measure positron drift velocities, $w$, (speed, $w$) in gases. Two main approaches have been used, and we will summarise them here and give some general remarks. However, we note at the outset that, at least to date, the main experimental difficulty has been in getting suitable drift lengths and times to compute $w$ using systems in which the positrons are derived directly from a radioactive source in a similar fashion to the lifetime experiments described above.

![Figure 4](image-url)

**Figure 4.** Schematic illustration of half of the positron drift apparatus developed by Paul and co-workers [31-33] Labelled are the source (S), a grid (G) and guard rings (R), the thin annihilation target (T) and a section of the viewing volume (V) defined by the apertures (A) in the lead wall.

3.1. Paul’s method
This is the technique developed by Paul and co-workers [31-33], as adapted from the pioneering work of Rodionov et al. [34, 35]. Paul’s system is shown schematically in figure 4. Positrons from two $^{58}$Co sources (only one of which is shown in figure 4) were confined along the axis of a drift system, of total length around 4 cm, by a 0.12 T magnetic field. A small fraction of the positrons thermalised in the
gas, which was typically at pressures of 100 Torr or lower ($\rho \sim 0.1$ Amagat). Drift was terminated by annihilation on a thin foil (to reduce annihilation of unmoderated positrons from the sources) in the centre of the cell such that the maximum drift distance, $l_m$, was about 2 cm. The foil was viewed by gamma-ray detectors in coincidence, via a lead collimation system, to reduce counts from other regions and the sources.

The coincidence data of Böse et al. [32] for H$_2$ at pressures in the range 10-200 Torr are shown in figure 5. It can be shown that the fraction, $F_d$, of positrons that drift into the foil after stopping in the gas [31] is given by

$$F_d = \left(\frac{w}{\lambda_d L_d}\right)[1 - \exp(-\lambda_d L_d/w)]$$

such that fits to the data shown in figure 5 yielded the parameter $w/\lambda_d$. The latter, expressed as $w/Z_{eff}$ is plotted in figure 6, along with $w$ derived using the known annihilation rate in H$_2$ from the accepted $Z_{eff}$ value, though only at zero electric field.

Figure 5. Relative coincidence curves versus applied electric field (here density-normalised as $\varepsilon/N$, rather than $\varepsilon/\rho$) for the detection of positrons drifting into the foil target in Paul’s apparatus. The data are for H$_2$ gas at various pressures (as marked by “H” numbers) between 10 and 200 Torr.
The parameter \( w/Z_{\text{eff}} \), which is proportional to \( w/\lambda_{f}l_{d} \), and the positron drift speed \( w \) (see text) for \( H_2 \) as derived from the coincidence curves shown in figure 5 plotted versus density-normalised electric field. The crosses are drift speeds for electrons in similar conditions.

The form of these curves has been explained in terms of positronium formation, which is also responsible for the downturns in the coincidence curves shown in figure 5. If the positrons have chance of being sufficiently heated that their kinetic energies might exceed \( E_{\text{Ps}} \), then they are very likely to form positronium and be lost. This is, in effect, a reduction in \( w \), since the positron stops drifting, akin to the effect of negative differential conductivity as explained by Petrović and co-workers [2-4]. However, in this experiment, in which the clock to time the drift is provided by the positron annihilation rate, this seems to be equivalent to an increase in \( \lambda_{f} \). In any case, flux is lost, and at high enough \( \varepsilon/\rho \), virtually no positrons can drift to the foil.

3.2. Charlton’s method

This method used the thin plastic scintillator timing technique, described briefly in section 2.1, together with a roughly 1 cm drift cell, which also formed the gas chamber [36, 37]. A gamma-ray detector was used to monitor positron annihilations in the cell, and with an electric field applied, some positrons annihilated prematurely, following drift to one of the electrodes. Thus, the free positron component was field dependent [38], and in particular was terminated at a time \( \tau_{\text{md}} \), a maximum drift time. This was due to positrons which had drifted across the entire length, \( l_{d} \), of the cell. Thus, the drift speed was given by \( w = l_{d}/\tau_{\text{md}} \), such that the positron mobility could be found from

\[
\mu_{+} = l_{d}/\tau_{\text{md}} \varepsilon.
\]  

A small sample of molecular gases was studied at room temperature using this technique and examples of lifetime spectra showing the effect of \( \tau_{\text{md}} \) are given in figure 7(a). Extracted drift velocities for \( O_2 \) and \( CO_2 \) are shown in figures 7(b) and (c). However, in many cases it was difficult to locate \( \tau_{\text{md}} \), such that the derived mobilities are only (statistically) accurate to about 15%. The timing spectra were dominated by the annihilation of positrons in the metal walls of the gas chamber, and very weak sources (and the efficient \( \beta^+ \) counting technique) had to be used in the fight to preserve signal-to-background. Thus, it would not easily be possible to scale this experiment up in terms of source activity or drift length (which would make \( \tau_{\text{md}} \) even harder to locate). It may, however, be possible to extract further information from this type of experiment by utilizing the entire positron lifetime component [38], rather than just relying on the determination of \( \tau_{\text{md}} \).
Figure 7. (a) Examples of positron lifetime spectra for CO$_2$ [36] at various density normalized fields illustrating the effect of the maximum drift time. The line drawn on the lower panel is a schematic of the zero-field spectrum at the density of 0.26 Amagat used in the experiment. (b) Drift velocities for O$_2$ at various $\varepsilon/\rho$ for pressures of 600 Torr (full circles) and 400 Torr (open circles). (c) Drift velocities for CO$_2$ at various $\varepsilon/\rho$ for pressures of 200 Torr (full circles) and 100 Torr (open circles). The full line is for the behaviour of the drift velocities for electrons in the corresponding range of $\varepsilon/\rho$ (CO$_2$ only).

A compendium of mobilities measured using this technique has been presented elsewhere [1], and the interested reader is referred there, and to the primary sources [36, 37] for further information and discussion.

3.3. General remarks
Let us take an example to explore the challenges faced by the two techniques discussed above. Assuming a pressure ~ 100 Torr at room temperature, which corresponds to a density of about $\rho \sim 4 \times 10^{24}$ m$^{-3}$ (or just over 0.1 Amagat) and taking H$_2$, with $Z_{\text{eff}} \sim 14$ as an example, results, using (3), in $\lambda_f \sim 0.03 \mu$s$^{-1}$, corresponding to a free positron lifetime of about 30 $\mu$s. Thus, for typical positron drift speeds $w \sim 10^5$ cms$^{-1}$, the drift distance in a lifetime will be around 3 cm. This explains the drift cell dimensions used in both of the experiments described in this section. Indeed for the work of Charlton, which typically operated at higher densities, shorter drift times were necessary to try to keep the signal-to-background manageable in the lifetime spectra.

To date, direct drift velocity data only exist for a few molecular species: this is due to the need to avoid non-thermal effects. The latter, as described in section 2, have been observed in several gases, most notably the nobles (see figure 1 and accompanying discussion). We can parameterise by introducing the density-normalised thermalisation time, $\tau_{\text{th}}\rho$, which is around 14 ns-Amagat for N$_2$, about 3 ns-Amagat for H$_2$ and well under 1 ns-Amagat for other molecules [1, 11, 15]. Thus, for molecules at a density of 0.1 Amagat, we find $\tau_{\text{th}}$ just over $10^{-7}$ s, which is negligible in comparison to expected drift times.

However, a better figure of merit here is $X = \tau_{\text{th}}\rho/\tau_f$. For C$_2$H$_2$, $X \sim 2 \times 10^{-4}(\tau_{\text{th}}\rho)Z_{\text{eff}}$, which is the ratio of the thermalisation time and the positron lifetime. We have $X \ll 1$, which is the desired situation, for all molecular gases, but things are not so straightforward for the nobles, as table 1 shows.

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Table 1. The figure of merit $X$ (see text) for the nobles and selected molecular species: $\tau_\text{th} \rho$ and $\tau_f \rho$ are in units of ns-Amagat.

| Gas  | $\tau_\text{th} \rho$ | $\tau_f \rho$ | $X$  |
|------|----------------------|----------------|------|
| He   | 1700                 | 1270           | 1.3  |
| Ne   | 2300                 | 830            | 2.8  |
| Ar   | 360                  | 190            | 1.9  |
| Kr   | 325                  | 75             | 4.3  |
| Xe   | 180                  | 12             | 15   |
| H$_2$| 3                    | 340            | 0.009|
| N$_2$| 14                   | 160            | 0.09 |
| CO$_2$| 0.1                 | 94             | 0.001|
| SF$_6$| 0.1                 | 51             | 0.002|

Thus, great care will be needed to perform and analyze the results of drift experiments on pure noble gases.

It has recently been suggested [39] that it may be beneficial to borrow from positron beam technology and incorporate a robust metal moderator (see section 4.1) into the drift cell to produce eV-energy positrons from a localized source. The surface of, for instance, an annealed polycrystalline tungsten moderator seems to be very inert. They have been routinely used in gassy environments, and can be left at atmospheric pressure for long periods (after annealing), and still found to operate on insertion into a beamline. We can estimate the flux of moderated positrons and compare this to that stopped directly in the gas. Thus, if we assume a moderator efficiency of $\epsilon_m \approx 10^{-4}$, which is typical for a polycrystalline sample, how does this compare to the efficiency, $\epsilon_g$, of positron stopping directly in the gas?

The $\beta^+$ implantation coefficient, $\mu_{\text{imp}}$, is given by $\mu_{\text{imp}} = 1.7 \rho/E^\text{1.14}_{\text{m}}$ (m$^{-1}$) (e.g. [40]), where $\rho$ is the medium density, now in kgm$^{-3}$, and $E_m$ is the endpoint energy of the spectrum of the particular isotope in MeV. For $^{22}\text{Na}$, $E_m \approx 0.545$ MeV, so upon converting the density into Amagat and using mass number, $A$, we find $\mu_{\text{imp}} \approx 0.15A\rho$ (m$^{-1}$).

To estimate $\epsilon_g$ for positrons which stop in a distance, $d$, say, we use a simple one-dimensional approach, which will underestimate the true fraction. It is easy to show (see e.g. [1]) that here $\epsilon_g \approx 1 - \exp(\mu_{\text{imp}}d)$, which is approximately $\mu_{\text{imp}}d$, since typically $1/\mu_{\text{imp}} >> d$. Taking our H$_2$ example from above, $A = 2$ and $\rho = 0.1$ Amagat, we find, with $d = 2$ cm (roughly the Paul cell drift length), $\epsilon_g \approx 6 \times 10^{-4}$. Thus, even in this unfavorable case of low $A$, $\epsilon_g$ is still comparable to, or bigger than, $\epsilon_m$. For SF$_6$, at the other end of the scale, $\epsilon_g$ will be of order 4-5%. Thus, using a moderator in a gas cell appears to offer few benefits.

4. Trapping, accumulating and manipulating positrons – new synergies for positron transport

In this section we will briefly discuss how positrons can be trapped, accumulated and manipulated in special systems, and how positron transport plays a crucial role in the underlying physical processes. Although there are several techniques by which positrons can be accumulated in high vacuum (see e.g. [41], where these methods are reviewed), here we will describe just one, the buffer gas accumulator. This is the most efficient positron accumulator and was pioneered by Surko and co-workers [42-44]. In order to appreciate the operation of this type of instrument it is first necessary to provide a brief introduction to positron beams. The interested reader can find much more information on this latter topic elsewhere; see e.g. [1, 45, 46].

4.1. Positron beam primer

The use of materials to moderate the kinetic energy of positrons emitted from radioactive sources has a long history. It has been found that certain materials, when appropriately treated, can emit positrons at low energy (typically of order eV) into vacuum. The mechanisms responsible for this effect are well
understood [45]. These either involve emission after thermalisation in the material from a surface with a negative work function for positrons (e.g. metal moderators, such as tungsten discussed above), or emission at epithermal energies from materials with a positive positron work function. The prime example of the latter are the solid rare gases and solid neon [47, 48] is the most efficient positron moderator to date, with a conversion efficiency from β⁺ particles to “slow” positrons in vacuum of around 1%. Thus, with ²²Na sources typically available with GBq activities, it is possible to obtain positron beams with intensities of several millions per second.

An example of a positron beamline is shown in figure 8, and it is the apparatus, with a 2-stage accumulator, which is currently in use at Swansea [49]. The detailed practicalities need not concern us here, but the energy of the beam can be altered, typically in the range 50-100 eV in this case, by applying a bias voltage directly to the neon moderator, which is plated onto a cold finger arrangement held in vacuum. The beam is guided along the axis of the system using magnetic fields provided by an array of coils and solenoids. Such beamlines are used for a variety of physics investigations, mainly in atomic and condensed matter physics [1, 46]. The controlled low energy beam also means that the positrons can be trapped and accumulated, as will be described below.

Figure 8. Cutaway diagram of a low energy positron beamline [49] showing the arrangement of source end coldhead (CH) lead shielding (LS) and ²²Na source (NS), the coils and solenoids (FMC, MC and TS¹ and TS²) to confine the beam onto the axis of the system and the two-stage buffer gas positron accumulator (PA). The pumping crosses are labelled C1-3 from left to right and are pumped by turbopumps (TP and MTP) and a cryopump (CP). Vacuum pressure and constitution can be monitored by cold cathode gauges (CC) and a residual gas analyser (RGA).

4.2. Trapping and accumulation of positrons
The low energy positrons are directed into a Penning Malmberg-type trap in which they interact with deliberately introduced nitrogen gas. An example of a 3-stage system, of the type developed by the UCSD group [42] and used at CERN for the formation of cold antihydrogen [6, 7], is illustrated schematically in figure 9. The three stages are formed from different diameter cylindrical electrodes and with nitrogen gas admitted to the centre of the narrow first stage, a pressure gradient is established, with, in the third stage, the pressure being around 10⁻⁶ mbar.

The on-axis electrical potential is also shown in figure 9 (lower panel) and, following energy loss of the positron as it undergoes an inelastic scattering event (excitation) with the nitrogen gas, forms the axial confinement for the particles. Radial confinement is provided by an axial magnetic field,
typically of around 0.15 T in strength. The positrons are trapped after they lose energy in stage 1 (N₂ has a strong positron excitation channel at around 9 eV, which competes effectively with positronium formation [50]) and eventually perform further excitations in stages 2 and 3 before slowing to thermal energies, which is room temperature in the studies to date. Thus, positrons from a quasi-continuous beam are accumulated into the low pressure, third stage, of the trap. Efficiencies can be of order 30% of the incoming beam [44, 49], such that it is possible to accumulate over 1 million positrons per second in this manner.

Figure 9. Three-stage positron accumulator [6, 7]. The pressures of the buffer N₂ gas in the three stages are given. The on-axis electrical potential of the Penning Malmberg trap is also illustrated. Radial confinement is provided by an axial magnetic field of 0.15 T in this instrument. One of the electrodes in the third stage is segmented for application of the rotating wall (see text).

Accumulation curves for the number of positrons, \( N(t) \), at a given accumulation time are shown in figure 10, and they follow the form,

\[
N(t) = N(\infty)[1 - \exp(t/\tau)],
\]

with \( N(\infty) = R_+\tau \), where \( R_+ \) is the rate of accumulation of the positrons and \( \tau \) is the positron lifetime in the trap. Note that in the three stage trap it is possible, with care, to obtain positron lifetimes of around 100 s, which is useful for studies which require large instantaneous fluxes of positrons [6-8]. (Note that the third stage can be in a separate vacuum chamber, and be fed repeatedly using a two-stage device, as was the case with Cassidy and Mills [8].) However, many applications can be envisaged for two-stage devices, with accumulation times of a second or less, and there are several such operating devices around the world [8, 49, 51]. Here typically \( 10^4-10^5 \) positrons will be accumulated before being ejected for further experimentation.

Figure 10 shows two accumulation cases for the ATHENA/ALPHA three-stage apparatus [52], one of which has a rotating electric field applied to one of the trap electrodes in stage 3, which has been segmented for that purpose. The effect of this will form part of the topic of the following sub-section.

4.3. Manipulation of trapped positrons

We start our discussion with the three-stage trap. Here, there are typically so many positrons accumulated that they form a plasma, a so-called single component, or non-neutral plasma. The behaviour of electron clouds held under similar circumstances to the positrons now forms a long established branch of plasma physics [53]. It was from this field that the rotating electric field, now
known as the rotating wall, was developed to counteract plasma expansion [54]. From a comparison of the plots of figure 10 for rotating wall on and off, it is clear that there is a beneficial effect from the wall, which increases the positron lifetime in the gas. (Note that for these measurements, the rotating wall is applied for the entire accumulation period.) From the results of other experiments with this apparatus which examined the behaviour of the positron lifetime as the nitrogen gas pressure is reduced, it is clear that the difference between field on and off is dominated by cross-field transport due to collisions with the nitrogen gas. We have observed similar effects in our two-stage accumulator at Swansea, though on shorter timescales, since the gas pressure is much higher.

![Figure 10](image)

**Figure 10.** Number of positrons accumulated versus storage time. The open circles are for accumulation without operation of the rotating wall, whilst the latter is switched on for the duration of the accumulation time for the closed circles. See text for details.

The basic physics of the rotating wall can be understood by recalling the behaviour of a non-neutral plasma in a Penning Malmberg trap, which has a uniform axial magnetic field. The radial self electric field due to the plasma, which is proportional to the distance from its centre, \( r \), combined with the axial magnetic field results in an \( E \times B \) drift velocity which is thus proportional to \( r \). This means that the plasma rotates about its axis with a constant angular frequency, \( \Omega \). Applying the rotating wall at a frequency greater than \( \Omega \), in the same sense as the natural rotation, leads to compression of the plasma due to the conservation of angular momentum. Further details of the mechanisms underlying the technique have been explored, primarily by the UCSD group in recent years [55-57].

The application of a rotating electric field to the plasma will cause heating, unless there is a mechanism to introduce cooling. In the ATHENA/ALPHA accumulator, in which the weak rotating wall is applied continuously, the cooling provided by the nitrogen buffer gas is sufficient to prevent excessive heating of the positrons. Systems which employ strong magnetic fields (~ T) in their traps, for instance one of the UCSD traps [58] and the mixing trap region of the ATHENA/ALPHA antihydrogen experiment [7], sufficient cooling is provided for electrons and positrons by the emission of synchrotron radiation. However, if the rotating wall is applied to compress the plasma after accumulation is complete, a strong drive is needed. Given the relatively poor positron cooling capabilities of \( N_2 \) (see table 1), an extra gas is needed to achieve compression. \( SF_6 \) is often used for this purpose, since it is a strong positron cooler, but has a relatively low \( Z_{\text{eff}} \) (97 at room temperature [1, 10]); i.e. it has \( X << 1 \).

Thus, it is also important to understand the positron transport properties of \( SF_6 \). Optimisation of rotating wall performance is usually carried out experimentally by trial and error. Guidance from
theory to help understand limitations to the technique, or perhaps point to directions for improvement would seem to be timely and important.

Further notable work by the Surko group has been done in extracting beams of positrons from their accumulator [59-61]. Such beams have a number of advantages over those typical of emission direct from a moderator. First, the positrons have been cooled to the temperature of the buffer and cooling gases, so the beams are typically of narrow energy width [59]. Furthermore, short time-width pulses containing \( \sim 10^5 \) positrons can be obtained using a pulsed extraction technique [62]. In addition, if the extraction is done with carefully adjusted voltage levels, the pulses will be preferentially extracted from the centre of the cloud, which is at the highest potential energy. In this manner narrow beams (so far down to \( \sim 50 \) \( \mu \)m in diameter) can be obtained [61]. Once a pulse has been extracted, the plasma quickly relaxes, refilling its centre such that the process can be repeated. Such pulsed micro-beams may prove useful in next generation positron drift experiments, as will be discussed in section 5.

So far, all the discussion has centred on manipulation of positron plasmas. In two-stage accumulators, for instance, it is typically not possible to collect positrons at a sufficiently high density to enter this regime. If rotating wall compression as described above is attempted in such systems there is no effect, perhaps other than positron loss via ejection from the trap.

However, very recently, a new rotating wall regime has been discovered which allows compression of pre-plasma clouds of positrons [63, 64]; i.e. the technique can be applied in the so-called single particle regime, where collective plasma effects can be ignored. As illustrated in figure 11(a), Greaves and Moxom [64] have shown that the central density of a positron cloud can be increased by about two orders of magnitude. Furthermore, figure 11(b) illustrates that the timescales needed for compression are in the ms range [64]. Again the cooler gas SF₆ is needed to observe the effect. Similar compression has recently been achieved in the Swansea two-stage accumulator [65].

The mechanism by which the rotating wall influences the particles and compresses the cloud is not clear at the time of writing. However, it is known that the rotating wall needs to be operated at a frequency at, or close to, the axial bounce frequency of the particles in the trap for compression to occur. Particles which have cooled to near the bottom of the potential well in a Penning-Malmberg trap will experience a local harmonic potential. As such, the axial frequency is well defined and is given by,

\[
\nu_a = \left(\frac{eV_t}{md_t^2}\right)^{1/2}/2\pi,
\]

where \( V_t \) and \( d_t \) are trap parameters, respectively the electrical depth and length of the trap. For positrons and electrons (mass, \( m \) and charge, \( e \)) this frequency is typically in the MHz range. By systematically varying trap depth to change \( \nu_a \), Greaves and Moxom [64] were able to show that the effect was caused by coupling to the positrons at their axial frequency and they speculated that an effect known as bounce resonance transport was responsible. Here, the combination of the axial bounce and azimuthal drift motions of particles causes them to move into resonance with an applied asymmetry. Some work has been done on this for electron plasmas [66-68], but further work is urgently needed, since the technique seems to have the promise to revolutionise positron beam physics by allowing cold, narrow beams to be available using relatively simple apparatus.

5. Possibilities for beam-based positron drift experiments

The first suggestion that positron drift experiments could be done using a low energy positron beam seems to have been made by Charlton and Jacobsen [69] in an article discussing applications of pulsed, accelerator-based beams. Unfortunately few of these beams were built, and even fewer were used for atomic physics work, and to the best of our knowledge, positron drift measurements have never been attempted using a positron beam as a source.

The idea of the proposed measurement was simple. Since the magnetically-confined pulsed beams envisaged at that time contained about \( 10^5\text{-}10^6 \) positrons per pulse, over a diameter of typically 1 cm, a 0.1 mm aperture into a cell containing gas at a pressure of several 10’s of Torr of gas was envisaged,
both to define the gas, and attenuate the beam. Charlton and Jacobsen [69] discuss various other technicalities of the experiment (including non-thermalisation effects in nobles), but the principle outlined was straightforward. The experiment was to rely on timing between the machine pulse and a particle detector located after the exit of the cell. Anticipating later work, [69] noted that the output of the gas cell would form a pulsed, cooled beam.

![Figure 11](image_url)

**Figure 11.** (a) Illustration of compression of positron clouds in the single particle regime as evidenced from the marked increase in central density (open circles versus the closed) of the positrons extracted from an accumulator [64]. (b) The timescales for compression of a cloud of positrons illustrated by the variation of the central density of the cloud at various times after the start of the rotating wall for various peak-to-peak applied voltage amplitudes, $V_{pp}$.

Whilst it is disappointing that some much early enthusiasm in the positron field was unfulfilled when intense beams, by and large, failed to appear, we have, as outlined in section 4.3, fresh cause for optimism. The new techniques which can be used to create pulsed, micro-beams, which are thus naturally timed (or can be further gated if the precision is insufficient) and which can be injected via a narrow aperture into a gas cell, seem to hold much promise. Indeed, the experiment suggested in [69] would seem, with small modification, to be suitable for use on the output of an accumulator, operating with rotating wall compression and employing the UCSD micro-beam extraction system. It should be recalled that all of the suggested experiments require confinement and transport of the beam using an axial magnetic field.
There may also be a further alternative, if a micro-beam and associated apparatus is not available. This involves taking a pulsed output from a two-stage accumulator and injecting it, through a thin foil, into a gas cell. In this case the beam would have to be injected into a Faraday cage-type system containing the cell such that the beam energy was raised to say 20 keV. Such acceleration systems are in routine use in positron labs around the world, mostly for depth-dependent condensed matter studies (see e.g. [46]), and there are plans to incorporate such a feature into a beamline at the ANU, Canberra [70], where there is a distinguished tradition of interest in swarm physics.

First we will explore positron implantation to see what thickness of foil might be needed to allow injection into the cell. Fortunately, there have been many studies of positron stopping in materials over the years and implantation profiles, \( P(z) \), are well understood. Without going into technicalities, the profiles can be reasonably accurately described by a Makhovian of the form [45, 46],

\[
P(z) = (mz^{-1/2}z_{o}^{m}) \exp(-z/z_{o}^{m}), \quad (14)
\]

with \( m \) a constant, the so-called shape parameter, and equal to 1.9. (Note here the different use of \( m \) from earlier in this article.) Here \( z_{o} \) is given by

\[
z_{o} = \langle z \rangle / \Gamma(1/m + 1), \quad (15)
\]

where \( \langle z \rangle \) is the mean implantation depth and \( \Gamma \) is the gamma function and is of order unity here. Thus, for our purposes, \( z_{o} \sim \langle z \rangle \), which can be written in the form \( \langle z \rangle = A_{mat}E^{n} \), where \( A_{mat} \) is a material-dependent constant and \( E \) is the positron impact energy. It turns out, empirically, that this can be approximated by,

\[
\langle z \rangle = 40E^{1.6}/\rho \quad \text{(nm)}, \quad (16)
\]

with \( E \) in units of keV and \( \rho \) in g cm\(^{-3}\). Inserting 20 keV as a kinetic energy and using \( \rho = 2.3 \) g cm\(^{-3}\) (for carbon) we find \( \langle z \rangle \sim 2 \) \( \mu \)m. Whilst this might appear to be thin, vacuum separation has been reported using very thin supported carbon foils [71]. Conductances as low as \( 10^{-3} \) ls\(^{-1}\) per cm\(^{2}\) were reported for foils as thin as 0.1 \( \mu \)m. Presumably thicker foils will have even lower conductances, such that adequate pressure differences between the cell and the surrounding chamber can be achieved. Indeed, depending upon the pressure required in the cell, issues concerning foil fidelity would need to be addressed first, though comments in [71] would appear to offer hope.

In the situation in which the positrons are injected through a foil it is likely that many will annihilate therein, resulting in a large prompt signal. However a downstream annihilation detector, which can be used to monitor the drift time, can probably be selectively sensitised by being switched “on” using a pulsed bias voltage only after the injection peak is over.

6. Conclusions

In this article we have reviewed positron transport in gases, a topic which has been studied since the earliest days of positron annihilation physics. In particular, we have detailed the attempts which have been made to extract drift velocities and mobilities from investigations of positron behaviour in small gas cells under the influence of applied electric fields. We have identified new areas where understanding positron transport is of current relevance for positron trapping, accumulation and manipulation in positron beam systems. We have suggested how trapped positrons might be used in future to make positron drift velocity measurements using new, and potentially versatile, techniques. New theoretical studies of positron transport in gases have also provided a fresh and timely impetus for experiment in this area.
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