EDITORIAL

Special issue on antihydrogen and positronium

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Editorial

Special issue on antihydrogen and positronium

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Since its prediction and discovery nearly 90 years ago, the positron (e⁺) has been the object of fascination, exploration, manipulation and application. Its arrival, when Dirac first successfully united quantum mechanics with special relativity [1], ushered in a new era in physics in which it became important to understand particles (including those comprised of antimatter) and their interactions, and the symmetries that underpin their nature and behaviour. Advances over many years in particle physics led to the development of the so-called Standard Model in which the role of antimatter is innate.

What this model tells us is that the properties of particles and antiparticles should either be identically equal, or equal but opposite. Thus, the positron and the electron (e⁻) should have the same rest mass, but opposite charge. Furthermore, composite antimatter systems, such as the antiproton, p, should have properties similarly related to those of the proton (p) whilst atoms and anti-atoms (and here we are principally concerned with hydrogen, H, and antihydrogen, \( \bar{H} \)) should have, for instance, identical spectral properties. And so far, whenever we have checked, we have found these symmetries to be obeyed to the measurement precision (see, e.g., [2] for a recent review).

However, behind this cozy understanding lies a puzzle. The standard model, our best theory of particle physics, cannot explain why the universe appears to be almost devoid of antimatter. An equivalent expression of this is that we do not understand why there is a material universe for us to observe and inhabit, since the matter and antimatter created in the big bang should have (almost) completely mutually annihilated leaving a universe comprised mainly of photons. That this is clearly not the case is a major motivation for many current particle physics investigations, and it provides one of the bases for the study of \( \bar{H} \).

That an \( e^+ - e^- \) bound state could exist was pointed out shortly after the discovery of the positron [3], and was soon known as positronium, Ps [4]. Interest awoke with its discovery and the ensuing seminal investigations of some of its properties by Deutsch and co-workers [5–7]. A major motivation for the study of Ps is that it is the paradigm system for bound state quantum electrodynamics (QED) since there are no hadronic complications due to the structure of heavier particles (for example the ongoing puzzle concerning the size of the proton [8, 9]). Over the years particular attention has focussed on its spectral and annihilation lifetime properties, and QED theories are now able to calculate some quantities for comparison with experiment to order \( \alpha^3 \) in the fine structure constant, \( \alpha \).

Most of the early work with Ps was done by allowing \( \beta^+ \) particles from a radioactive source (typically \(^{22}\)Na, with its high \( \beta^+ \) fraction and convenient 2.6 y half life) to slow directly in the sample under study, which was usually a gas of some kind held at densities around 10\(^{22}\)–10\(^{23}\) m\(^{-3}\). The restriction imposed by using radioactive sources in this way (for instance, the lack of control of the kinetic energy of collisions and the need to use dense samples to ensure that a reasonable fraction of the \( \beta^+ \)s were stopped) were appreciated by many, and motivated the search for a method to produce controllable beams of \( e^+ \) at low energies. Pioneering works [10–13] eventually led to the discovery that a smoked
sample of magnesium oxide held in vacuum emitted a small fraction (around \(10^{-5}\)) of the incident \(\beta^+\) flux in the eV range, which could readily be transported as a beam [14].

A deeper understanding of this phenomenon, now known as positron moderation, was quick to follow (see, e.g., [15, 16] for reviews), and beam production efficiencies now stand at around the 1% level [17] which, coupled with the commercial availability of vacuum-compatible radioactive sources with activities in the GBq region, has led to low energy \(e^+\) beams with fluxes of around \(10^6–10^7\,\text{s}^{-1}\). The ability to manipulate \(e^+\) at low energies enabled positron trapping to be effected, principally by Surko and co-workers [18, 19], using buffer-gas devices. Here positron–molecule collisions were used to enable accumulation of \(e^+\) in so-called Penning–Malmberg traps (which achieve charged particle confinement using electric and magnetic fields) for further experimentation. The latter involved extraction in cold beams—the trapped \(e^+\) have time to thermalise to the buffer gas (room) temperature—and in pulsed form, sometimes containing in excess of \(10^8\,e^+\) in bursts a few nanosecond wide. The output of such traps can be tailored for the particular application. One of these is the accumulation of (numerically) large clouds to promote \(\bar{H}\) formation [20], and Fitzakerley et al [21] have reported the collection of a record \(4 \times 10^9\,e^+\) in a cryogenic, extreme high vacuum Penning-like trap. This trap was fed by intense bursts from a buffer gas device, with the trapped \(e^+\) rapidly electron-cooled to allow the full loading capabilities of the instruments to be exploited. Should the \(e^+\) be required in a magnetic-field free region, Cooke et al [22] have described how time-compressed pulses can be extracted from an accumulator and focussed into a 1 mm spot using a pulsed acceleration device.

The beam and trap capabilities have opened up many areas of science. A non-exhaustive list includes: variable energy positron scattering from atoms and molecules; the formation and application of quasi-monoenergetic Ps beams; laser spectroscopy of Ps; the formation of, and experimentation with, antihydrogen; the formation of the Ps negative ion, and the Ps molecule Ps_2; the development of \(e^+\) spectroscopy as a surface, near-surface and interface probe in the solid state. This is a very wide arena, stretching all the way from particle physics to materials science, and many of the aforementioned sub-disciplines are represented in this rich and varied collection.

One application of intense ns \(e^+\) bursts is the creation of Ps clouds in vacuum when the \(e^+\) are allowed to impinge upon a target. Several groups have combined this capability with pulsed laser systems (e.g., [23–28]) which has allowed the production of Ps in a range of excited states, including so-called Rydberg states. In this issue Andersen et al [29] report Ps emission from a meso-structured thin silica film in which the Ps has been observed both in the reflection (whereby the Ps is emitted from the film on the side on which the \(e^+\) entered) and transmission geometries. The Ps is formed in the film with about an eV of kinetic energy, but then cools by collision in the pores before emission into vacuum. The emission properties of the Ps were elucidated by study of the Doppler-broadened Lyman-\(\alpha\) transition. Capabilities with Rydberg Ps continue to be explored and Jones et al [26] have used crossed-beam spectroscopy to uncover a notable dependence of the polarisation of the infrared laser on the transition rates from Ps states with principal quantum number \(n = 2\) to \(n = 30\), Stark split by motional effects in an applied magnetic field. Once excited into a high-lying state, the Ps annihilation lifetime is essentially infinite, which enabled Jones and co-workers to observe the eV-kinetic energy Ps using a channel plate detector at the end of a 1.5 m flight path.

Excited Ps atoms have long been suggested as a means to produce \(\bar{H}\) via the reaction \(\bar{p} + \text{Ps} \rightarrow \bar{H} + e^-\) [30], and this reaction was observed some time ago in a demonstration experiment performed by the ATRAP collaboration [31]. Here the excited Ps was prepared via a resonant charge exchange interaction between
laser-excited caesium atoms and a dense, cold positron cloud, and McConnell et al [32] have reported an increase in excited \( \text{Ps} \) flux by a factor of around 500 over the previous work [31], mainly due to improvements in positron trapping yields.

Major advances in the study of antihydrogen have taken place in the last years (see, e.g. [33, 34] for recent reviews), with the recent observation of the \( 1S \rightarrow 2S \) two-photon transition [35] being a particular highlight. Theory and simulations have played an important role over the years in assessing the viability of experiments, and in some instances in aiding in their interpretation: see [36] for a review. The ASACUSA collaboration is making progress towards a measurement of the \( H \) ground state hyperfine splitting using a beam of the atoms. The challenge is to get sufficient \( H \) flux in the ground state, and Radics and Yamazaki [39] and Lundmark et al [40] address different aspects of this, namely the role played by positrons collisions as a function of the length of the plasma and the effect of in-flight radiative decays from an initially excited state population produced via the three-body reaction \( p^- + e^+ + e^+ \rightarrow H^- + e^+ \). It is likely that we must await experiment to provide further guidance here.

In the \( H \) experiments performed to date all except that of Storry et al [31] have used the aforementioned three-body reaction which, at high enough \( e^+ \) cloud/plasma densities and low enough temperatures proceeds much more rapidly than radiative combination, and is characterised by formation of the anti-atom in weakly bound states [41]. Such states are highly susceptible to further collisions and the ambient fields present in the experiments [42]. These fields are often a result of the use of dense positron plasmas, something that has motivated Lane and Ordonez [43] to develop a model of \( H \) formation (and other \( p^- \) loss process) under conditions typical of those found in the ALPHA experiment in an effort to find optimum conditions for the rate of \( H \) formation via the three-body reaction. It turns out that radial transport of \( p^- \)'s is one such loss process which, as elucidated by Jonsell and co-workers [44], is strongly enhanced by the formation \( H^- \), since when bound in the neutral system, the \( p^- \) is no longer pinned radially by the strong magnetic field. This transport mode dominates over thermal diffusion whenever \( H^- \) can occur as many cycles of formation and destruction by collisions can cause a net outward flow of the \( p^- \)s.

Atomic scattering theory has frequently been brought to bear on problems of relevance to \( H \) formation and interaction, with a recent notable example of the former being the \( p^-\text{–Ps} \) work of Kadyrov and Bray and co-workers [45, 46]. This system has also been studied by Lazauskas et al [47], and in particular resonance structures which appear just below various thresholds. Unfortunately the features are probably too narrow to influence the experimental \( H \) production yield using \( p^-\text{–Ps} \) collisions. The antihydrogen positive ion, \( H^+ \) should, like its matter counterpart \( H^- \), have a single bound state. The GBAR collaboration aims to produce this entity via \( H^-\text{–Ps} \) interaction (see e.g., [48]), though direct radiative capture of the positron via interaction with ground state \( H \) as \( e^+ + H^- \rightarrow H^+ + h\nu \) is also a possible route. This was studied theoretically recently by Keating et al [49], with a refined calculation appearing in the present volume [50]. Anticipated production rates are, unfortunately, too low to be practical without increases in \( H^- \) trapping efficiencies.

With \( H^- \) now able to be trapped and held for long periods, its interaction with ordinary matter may become important and the \( H^-\text{–H} \) system has been studied for some time as a paradigm of its class (see [51] and references therein). This is a challenging 4-body quantum system, with important rearrangement channels into protonium (\( Pn \) the \( p^-p \) bound state) and \text{Ps}. This system has resonance structures located close to the \( H^-\text{–H} \) dissociation limit, as uncovered by Stegeby and Piszczerowski [51].

Though the creation of \( H \) is now relatively routine, given the superb resources and facilities provided by CERN, performing experiments to make precision
determinations of its properties will always be challenging, with a need to increase the yield of anti-atoms, whilst lowering their kinetic energies, seemingly the way forward. In the first demonstration of laser spectroscopy of $\bar{\Pi}$ [35] some of the anti-atoms were photoionised by the laser pulse, with the result that a $\bar{\Pi}$ was detected via its annihilation on the wall of the trap. Cesar [52] has proposed a method which should be more efficient, and involves storing the liberated $\bar{\Pi}$'s in a shallow Penning trap for later ejection and detection via a channel plate device, and has provided estimates of overall performance.

Measuring the gravitational interaction of systems containing antiparticles has emerged as an area of current interest, and experiments are planned on $\bar{\Pi}$ [53–55], $\Pi$ [48, 56] (where a methodology has already been developed [57]) and muonium (Mu, the $e^+$–positive muon bound state) [58]. These are all challenging: Ps and Mu have finite lifetimes, and though this does not apply to $\Pi$, the anti-atom is, for obvious reasons, in much shorter supply than either of the other two systems. Going beyond what is currently proposed for $\Pi$, Voronin et al [59] describe how ultra-cold $\Pi$ held close to a surface in the Earth’s gravitational field can form quantum states that can be used to engineer a ballistic free-fall situation with relative measurement precision approaching $10^{-4}$. There are formidable experimental challenges here, as the $\Pi$ temperatures must be around the $\mu K$ region.

The fundamental properties of Ps continue to be of interest, including the ground state hyperfine splitting. Recent work by Ishida and co-workers [60, 61] seems to have resolved small discrepancies that had developed between earlier measurements [62, 63] and more recent QED theory. Subtle effects related to the epithermal annihilation of ortho positronium in the gas samples used were found to be the cause of the effect, and can now be corrected for [61]. Dominant Ps vacuum annihilation modes involving the emission of gamma-rays have been widely studied, however Pérez-Ríos and Love [64] point out that electro-weak interactions will allow other processes to occur, and they provide a calculation of the decay into a single gamma, plus an neutrino–antineutrino pair. The rate for this reaction turns out to be around $2 \times 10^{-12} \text{ s}^{-1}$, which is likely to mean that it will be difficult to observe.

The possibility of achieving a Ps Bose–Einstein condensate (BEC), and some of the motivations for doing so, were discussed more than two decades ago [65] and since then much progress has been made producing dense Ps samples: see, e.g., [66, 67] for reviews. In this issue Shu et al [68] describe a new study of Ps cooling, including collisions with the walls of a silica cavity, the role of Ps–Ps interactions and the use of a bespoke broadband chirped, pulsed laser to efficiently cool using the 1S–2P transition at 243 nm, with the system seemingly under development. Challenges also exist in focussing the positron beam down onto a cool using the 1S

The desire to study controlled collisions of low energy positrons with atoms and molecules provided one of the main motivations for the development of low energy beams [70]. Over the years interest has shifted somewhat away from the intrinsic nature of positron collisions to their applications, for instance in biological systems. In this spirit, Machacek and co-workers [71] have found a simple functional form (a so-called surge function) which can be used to model total positronium formation cross sections for a number of atoms and molecules. Studies of positronium formation in $e^+–$alkali collisions has long been of interest due to the effective one-electron nature of the targets, and since the reaction into the Ps ground state is exothermic: a comprehensive list of references to this work has been given by Pandey et al [72]. These authors have studied $e^+$ collisions in the
1–500 keV range with the alkalis embedded in a Debye plasma, a situation that may be of astrophysical significance. The screening provided by the plasma has been varied, and found to lower cross sections at higher energies, but increase them below about 20 keV.

The exchange interaction between the $e^-$ in Ps and those in the atoms and molecules it collides with have been found [73, 74] to be at the root of observed similarities between $e^-$ and Ps scattering cross sections [75, 76], and Van Reeth et al [77] and Gribakin et al [78] both address this topic here. Van Reeth and coworkers use a Kohn variational technique to study at low energies (equivalent to speeds below 1 a.u.) $e^+$, $e^-$ and Ps elastic scattering from atomic hydrogen. Similarities between the $e^-$ and Ps angle-integrated cross sections are found over some velocity ranges, and that this is accentuated when one considers only the singlet contributions in both cases. Gribakin et al calculate cross sections for Ps elastic scattering and ionisation (i.e., here, break up), which are the dominant channels for rare-gas targets in the velocity range above about 1 a.u.. They find, in particular for Xe in this study [78], that the behaviour of the Ps and $e^-$ cross sections are of similar shape and magnitude.

The annihilation of Ps confined in porous media has proven to be of value in determining pore and void size using semi-empirical models that typically involve overlap of a single Ps with electrons in the material. Zubiaga et al [79] have described an extension to this model applied to the Ps–He system (where the He is at low temperatures and high pressures) in which a more realistic atomistic model of the host material is included, and find that they are able to compute, for example, accurate annihilation rates sensitive to the void size and the local electronic environment.

The input of theory to positron and positronium physics continues to be deep and fruitful. One parameter of interest is $Z_{\text{eff}}$, the so-called effective number of electrons that the positron ‘sees’ in an atom or molecule for annihilation. For a free (non-interacting) $e^+$, $Z_{\text{eff}} = Z$, the actual number of electrons. However this is hardly ever found to be the case, and dramatic instances in which $Z_{\text{eff}} \gg Z$ are now understood in terms of the formation of resonances in which the $e^+$ is temporarily bound to the molecule: see, e.g., [80] for a comprehensive review. For molecules, H$_2$ was always a test case, and with a room temperature $Z_{\text{eff}}$ of around 15, it took some years of effort by Armour and colleagues to understand this. In the present issue Armour and Plummer [81] evaluate, using a close coupling formalism, resonant contributions to the H$_2$ $Z_{\text{eff}}$ caused by vibrationally excited quasi-bound states, and find favourable comparisons with earlier work of Gribakin and Lee [82].

We close this discussion of the contents of the Special Issue by pointing out the two reviews that accompany the edition. The Topical Review of Kadyrov and Bray [83] covers recent advances in the treatment of positron scattering using the convergent close coupling (CCC) formalism. The CCC method has been one of the most successful theoretical treatments of positron scattering, particularity when (as with Ps formation) two centres are involved. Kadyrov and Bray present a comprehensive treatment of the state-of-the art, together with a full and useful bibliography. In a different vein, Karshenboim [84] has provided a brief, but useful overview of antimatter and the weak equivalence principle pointing out that current experimental data rule out what is sometimes called antigravity, and indeed already place constraints on the ratio of free fall acceleration of matter and antimatter at a level of a part in $10^5$.

The depth and variety of contributions to this special issue is a testament to the vitality of the field and how it continues to move rapidly, with new capabilities (such as ELENA, the upcoming 100 keV $\pi$ machine at CERN) continuing to allow more boundaries to be pushed. Going forward, the next 20 years are likely to bring us the Ps BEC, precision measurements of the spectral and gravitational
properties of Π, portable antimatter traps, production of positrons for applications using high power lasers and much else that we have not yet imagined.

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