# UK Positron Meeting 2024

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# Book of Abstracts

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**Positronium Physics / 21**

# Measurement of the positronium $2\,^3\mathrm{P}_J$ fluorescence decay rate

**Author:** Rebecca J Daly[1]

**Co-authors:** David B Cassidy ; Ross E Sheldon [2]

[1] *University College London*

[2] *UCL*

**Corresponding Authors:** d.cassidy@ucl.ac.uk, rebecca.daly.18@ucl.ac.uk, ross.sheldon.18@ucl.ac.uk

Positronium (Ps) decay rate measurements can be used to test QED theory [1], and in the search for new physics. Previous experiments have measured the annihilation decay rates of the ground states [2,3], and the excited $2\,^3\mathrm{S}_1$ state [4] of Ps. We report a measurement of the fluorescence decay rate of Ps atoms in the $2\,^3\mathrm{P}_J$ level using a new technique. By applying an electric field to metastable $2\,^3\mathrm{S}_1$ Ps atoms, we produced Stark-mixed states with both $2\,^3\mathrm{S}_1$ and $2\,^3\mathrm{P}_J$ components, and controlled their relative populations by varying the strength of the field. A larger electric field was subsequently applied to induce rapid quenching, and annihilation, of the mixed states. The number of quenched atoms across various mixing field strengths was measured, and these measurements, along with Monte Carlo simulations, were used to determine the decay rate of the $2\,^3\mathrm{P}_J$ state.

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**Positronium Physics / 7**

## Positronium density measurement technique using Polaritonics

**Author:** Erika Cortese[1]

**Co-authors:** David B Cassidy ; Simone De Liberato [1]

[1] *University of Southampton*

**Corresponding Authors:** erika.cortese91@gmail.com, d.cassidy@ucl.ac.uk, sdl2c12@soton.ac.uk

Positronium (Ps) is an electron-positron bound state forming in fact a meta-stable two-body atomic system. As Ps is bosonic, a long term goal of Ps physics has been the formation of an ensemble of Ps atoms cold/dense enough to create a Bose-Einstein Condensate (BEC). Its primary motivation is that such a system may exhibit the phenomenon of stimulated annihilation, allowing for the creation of a gamma-ray laser. Recent experimental advances in Positronium physics have made it possible to produce dense Ps ensembles confined within the voids of porous materials, paving the way to the realization of a Ps BEC. In order to achieve this latter goal it would be advantageous to develop new methods to measure Ps densities in real-time. Here we describe a possible approach to do this exploiting concepts of cavity quantum electrodynamics (CQED), the field that investigates the interaction between dipolar active transitions in atoms, molecules or other materials, and single photons inside an optical cavity. When the light-matter coupling strength becomes larger than the loss rates of the light and matter excitations, the system enters the so-called strong coupling (SC) regime, and it can be described only in terms of the light–matter hybrid eigenmodes of the coupled system, often named polaritons. Using realistic experimental parameters we demonstrate that a dense Ps gas, can be strongly coupled to the photonic field of a distributed Bragg reflector microcavity. In this strongly coupled regime, the optical spectrum of the system is composed of two hybrid Ps polariton resonances separated by the vacuum Rabi splitting, which is proportional to the square root of the optically active atoms, and as such can serve as a direct measurement of the Ps density. This phenomenology is demonstrated for the 1S ↔ 2P optical transition in the UV spectrum by employing AlGaN/AlN DBRs, and for transitions between Rydberg states ($n > 10$) coupled to a high-quality-factor DBR cavity in the mid- to far-infrared range. Given that polaritons can be created on a sub-cycle timescale, a spectroscopic measurement of the vacuum Rabi splitting could be used as an ultra-fast Ps density measurement in regimes relevant to Ps BEC formation. Moreover, we show that Ps-polaritons could also enter the ultrastrong light-matter coupling regime potentially exhibiting its rich phenomelogy, such as the presence of virtual excitations in the ground state and the possibility of modifying the Ps wavefunction.

In conclusion, the new found connection between positronium research and polaritonics not only solves one important problem in the path towards the achievement of Ps BEC, that is the ultrafast real-time measurement of the Ps population, but also offers to polaritonic scientists the unique opportunity of exploring non perturbative light-matter phenomena on a novel powerful polaritonic platform.

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# Similarity of the near-threshold cross-sections for positronium formation and photoionisation in polyatomic molecules

**Authors:** James Danielson[1]; Eugene Arthur-Baidoo[1]; Gleb Gribakin[2]; Clifford Surko[1]

[1] *University of California, San Diego*

[2] *Queen's University Belfast*

**Corresponding Author:** g.gribakin@qub.ac.uk

This work reveals a remarkable similarity between the near-threshold energy dependence of the positronium (Ps) formation and photoionisation cross sections for several polyatomic molecules. The Ps-formation cross sections have been measured using a high resolution (∼35 meV FWHM) trap-based positron beam for energies within a few eV of the Ps-formation threshold, $E_{\text{thr}} = E_I - |E_{\text{Ps}}|$, where $E_I$ is the target ionisation energy, and $E_{\text{Ps}} = -6.8$ eV is the Ps ground-state energy. Here we present the cross sections for aniline ($C_6H_5NH_2$), pyridine ($C_5H_5N$), and cyclopentane ($C_5H_{10}$). The cross section magnitude for pyridine are in agreement with earlier low-resolution data [1]. The Ps-formation cross sections are compared with measured photoionisation cross sections shifted to the Ps-formation threshold, with magnitudes scaled by a constant factor. This comparison shows that for each molecule, the two cross sections have a nearly identical dependence on the excess energy within a $1-2$ eV of the threshold. This similarity is contrary to the significant difference between the two processes. In Ps formation, the interaction between the slow Ps and the residual cation is of short range, while in photoionisation, the electron moves in the attractive Coulomb field of the ion. As a result, at the basic level, the Ps-formation cross section is expected to obey the Wigner threshold law $\sigma \propto (E - E_{\text{thr}})^{1/2}$, while the photoionisation cross section must have a step-like onset with $\sigma = \text{const}$ at threshold. We discuss possible reasons for this similarity. In particular, it appears that the observed near-threshold behaviour is governed by vibrational excitations of the molecular cation and Franck-Condon factors, rather than the energy dependence of the underlying leptonic cross sections. For pyridine, this explanation is supported directly by comparisons with high-quality theoretical data for the vibronic excitation spectrum intensities [2]. We also discuss where the similarity breaks down and in what other targets it can be expected.

We are grateful to A. B. Trofimov for providing the results of their calculations in numerical form, and for numerous useful discussions.

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**Positronium Physics / 4**

## Multiple Compton scattering of entangled photons produced by ground-state parapositronium disintegration

**Author:** Peter Caradonna[1]

[1] *University of York*

**Corresponding Author:** peter.caradonna@york.ac.uk

The effect of entanglement on the scattering distributions of Bell-state photons participating in multiple Compton scattering events is an open question. This study addresses this question by proposing a methodology to compute cross sections that, in turn, allow predictions to be made about the scattering distributions. The framework is applied to the Compton scattering of Bell states created through the disintegration of parapositronium in the ground state. The focus is on calculating the cross section for 3-Compton scattering events, where one of the photons undergoes intermediate Compton scattering, and then both photons are detected using Compton polarimeters operating in coincidence mode. The correlation amplitude that governs the strength of the azimuthal correlations between the scattered photons is analysed with respect to the intermediate scattering angle. The correlation amplitude exhibits various characteristics, including enhancement, reduction, sign inversion, or vanishes at specific intermediate scattering angles.

**Plasma related Physics / 16**

# Positron bunches & electron plasmas in supported & levitated dipole traps

**Author:** Adam Deller[1]

[1] *Max-Planck-Institut für Plasmaphysik*

**Corresponding Author:** adam.deller@ipp.mpg.de

Many of the instabilities that are common to magnetically confined ion-electron plasmas are expected to be suppressed in electron-positron "pair" plasmas. The goal of APEX (A Positron Electron eXperiment) is to create and confine a pair plasma by combining separate non-neutral plasmas of electrons and positrons. Challenges associated with this task include (i) the construction of a trap that can simultaneously hold the oppositely charged leptons, and (ii) the accumulation and injection of sufficiently many positrons to produce a neutral plasma. A compact, levitating dipole trap (LDT) has been built to magnetically confine pair plasmas, and long levitation (> 2 hr) and stable trapping of pure electron plasmas (> 2 s) have already been achieved. In parallel to the LDT development, a lossless E×B-drift technique was recently adapted to inject bunches of positrons into a supported dipole trap. The pulsed beam was used to study transport in the inhomogeneous magnetic field and to test schemes for merging collections of electrons and positrons.

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# Sympathetically cooled positrons for enhancement of antihydrogen production rate

**Author:** Maria Beatriz Gomes Goncalves[1]

**Co-authors:** Kurt Anthony Thompson [1]; Niels Madsen [1]; Nishant Mayank Bhatt [1]; Tom Robertson-Brown [1]

[1] *Swansea University (GB)*

**Corresponding Authors:** maria.beatriz.gomes.goncalves@cern.ch, niels.madsen@cern.ch, nishant.bhatt@cern.ch, thomas.robertson-brown@cern.ch, kurt.thompson@cern.ch

The ALPHA experiment produces and traps antihydrogen atoms by slowly mixing antiprotons and positrons in a Penning-Malmberg trap. Using various techniques, ALPHA measures many properties of these atoms, for example, their interaction with gravity [1], allowing for a comparison between antihydrogen and hydrogen. Accumulating a large number of atoms (in the order of thousands) is imperative for the increase in data-taking rate as well as for the decrease of statistical errors. Thus, increasing the amount of antihydrogen available for experimentation is key for improvements in our studies of fundamental symmetries.

Many efforts to increase the production rate over the years have demonstrated that one of the parameters that most influences it is the temperature of the positron cloud during the mixing process of the species. [2] Under the 3T region, cyclotron cooling allows the positrons to cool down to about 15K. This yielded a trapping rate of about 20 antihydrogen atoms every 4 minutes.

Using a laser-cooled Be+ cloud, we can sympathetically cool the e+ to cryogenic temperatures [3], in this work, we describe the development and implementation of this technique during antihydrogen production at ALPHA, resulting in an almost 5-fold increase in stacking rate.

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**Plasma related Physics / 15**

## Sources of positrons and protons

**Author:** Alina Weiser[1]

**Co-authors:** Andreas Lanz [2]; Daniel James Murtagh [1]

[1] *Austrian Academy of Sciences (AT)*

[2] *UCL - Department of Physics and Astronomy*

**Corresponding Authors:** alina.weiser@cern.ch, dan.murtagh@cern.ch, a.lanz@ucl.ac.uk

Positron and proton sources, and traps have played a pivotal role for the antimatter research taking place both in Vienna and at CERN as part of the ASACUSA collaboration.

At home in Vienna, we have designed and constructed a positron beamline which uses a conventional $^{22}$Na source and Ne moderator to produce a beam which is trapped and conditioned for experiments in a Surko-type positron trap [e.g. 1,2]. This beamline is currently being commissioned after final safety clearances for operation to use the source in a residential area. We first aim to use the positron pulses from this trap to observe molecules containing positronium, such as PsH [3] and PsO [4] via collisions in gases such as methane and carbon dioxide. By using a high-resolution ion mass spectrometer to detect fragments from dissociation, a precise measurement of their binding energy will be performed.

We have also designed, built and characterised a proton source [5] for the ASACUSA collaboration with the aim of performing matter mixing experiments when antiprotons are not available. Using electron impact ionisation, protons are created via dissociative ionisation of $H_2$ gas. A rotating wall electric field destabilises the unwanted $H_2^+$ and $H_3^+$ generated during the dissociative ionisation process, while concentrating the protons in the centre of the trap. The source produces bunches of protons with relatively low ion contamination (5.5 % $H_2^+$ and 15.5 % $H_3^+$), with energy tuneable from 35 to 300 eV, and has already been used to transfer protons into the 'Cusp'trap at CERN.

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**Plasma related Physics / 13**

# The ASACUSA Cusp experiment

**Authors:** Daniel James Murtagh[1]; Andreas Lanz[2]

[1] *Austrian Academy of Sciences (AT)*

[2] *UCL - Department of Physics and Astronomy*

**Corresponding Authors:** a.lanz@ucl.ac.uk, dan.murtagh@cern.ch

The ASACUSA-Cusp experiment aims to perform spectroscopy of the hyperfine structure of antihydrogen by producing a beam of cold, spin polarised, ground state antihydrogen. The beam will be produced by mixing positrons and antiprotons in our unique Cusp trap which uses a pair of superconducting coils in an anti-Helmholtz configuration to produce a magnetic field capable of both confining the charged particles radially and polarizing the antihydrogen atoms.

Thus far, the collaboration has observed antihydrogen 2.7 m from the production region [1] and measured the distribution of principal quantum number of these atoms [2]. This weak beam was not suitable for the spectroscopy measurement so work commenced on improving the beam intensity and skewing the distribution towards ground state atoms. Simulations showed that the route towards this aim was producing colder dense positron plasmas [3].

Recently, a major technological milestone was achieved by the collaboration. Antihydrogen produced via three-body recombination will have an isotropic distribution so a large open solid angle is needed for the antiatoms to escape. This has the disadvantage that the production region is illuminated by a hot (300 K) black body. Previously, it has not been possible to cool plasma below 130 K, however, a new electrode stack and coldbore with a focus on blocking microwaves from the room temperature region has allowed particles to cool to 25 K maintaining the large open solid angle for the beam to escape [4].

In this presentation I will discuss the methods used by the ASACUSA Cusp experiment to and give details on the most recent work on plasma handling and beam production in the new Cusp trap.

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**Poster Session / 24**

## Status of laser spectroscopy of antiprotonic helium at CERN

**Author:** Masaki Hori[1]

[1] *Imperial College London*

**Corresponding Author:** m.hori@imperial.ac.uk

Metastable antiprotonic helium is a neutral three-body atom [1-6] that contains a helium nucleus, an electron occupying the 1s state, and an antiproton in a Rydberg state of large principal (n≈38) and orbital angular momentum (l=n-1) quantum numbers. Whereas spectroscopy of antihydrogen atoms probes the interaction between an antihadron and antilepton, the antiprotonic helium atom is a hadron-antihadron quantum bound system having the longest known lifetime that can be readily produced. The ASACUSA collaboration at CERN will utilize the unprecedented high-quality beam of the ELENA facility and the latest laser metrology techniques to carry out sub-Doppler two-photon laser spectroscopy of narrow resonances of antiprotonic helium atoms. By comparing the results with three-body QED calculations the antiproton-to-electron mass ratio and upper limits on exotic forces that can arise between the constituent particles will be precisely determined.

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**Poster Session / 23**

# Laser-driven positrons sources for Positron Annihilation Lifetime Spectroscopy

**Author:** Temour Foster[1]

[1] *Queen's University Belfast*

**Corresponding Author:** tfoster06@qub.ac.uk

Positron Annihilation Lifetime Spectroscopy (PALS) is one of the most effective material analysis techniques at detecting sub-nanometer defects in materials. Current conventional PALS facilities use positron beams of low keV energies and long durations, resulting in poor penetration depth and durations similar to the annihilation lifetime (~150ps), therefore giving poor resolution. By using laser-driven positrons, tuneable MeV-scale energies can be attained with short durations (~30ps), improving both the resolution and allowing for volumetric studies. Here, preliminary experimental results using taranis at QUB will be shown, along with an outline of future investigations at ALFA

**Poster Session / 20**

# Polarisation Sensitive Microwave Spectroscopy of the $2\,^3\mathbf{S}_1 \rightarrow 2\,^{2S+1}\mathbf{P}_1(S = 0, 1)$ Transitions in Positronium

**Author:** Ross E. Sheldon[1]

**Co-authors:** David B. Cassidy [1]; Krzysztof P. Habdas [1]; Rebecca J. Daly [1]

[1] *UCL*

**Corresponding Author:** ross.sheldon.18@ucl.ac.uk

Precision spectroscopy of the positronium (Ps) $n = 2$ fine structure intervals has been performed several times to test bound state QED [1]. All previous measurements have used microwave waveguides with a fixed polarisation (e.g. [2,3,4]), and the effect of polarisation on these transitions has not been explored. The polarisation can change the subset of transitions driven by the radiation, changing Zeeman and Stark shifts, creating unwanted systematic effects.

We have used a horn antenna [5], which can be rotated to change the polarisation of the microwave radiation, to measure line shapes of the $2\,^3\mathrm{S}_1 \rightarrow 2\,^{2S+1}\mathrm{P}_1$ $(S = 0, 1)$ transitions. This was done in a large magnetic field to create large Zeeman splitting between the states, and to allow the $S = 0$ transition, which is forbidden by charge conjugation symmetry [6]. We report the effects of microwave polarisation on the resonance frequency and strength of the measured transitions. This work is a precursor to precision waveguide experiments which will measure these energy intervals as well as test for possible charge symmetry violation in the $S = 0$ transition.

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**Poster Session / 14**

# Measuring the Orthopositronium Annihilation Decay Rate

**Author:** Ivneet Bhangoo[1]

[1] *University College London*

**Corresponding Author:** ivneet.bhangoo.20@ucl.ac.uk

As a purely leptonic system, precise measurement of the properties of positronium (Ps) offers a unique avenue for testing bound-state QED theory and physics beyond the standard model if experimental uncertainties can match or exceed those of theoretical results. The decay rate of the triplet ground-state (o-Ps) due to annihilation has been determined to an experimental uncertainty of 100 ppm [1], two orders of magnitude larger than current theory (2.7 ppm) [2]. Previous experimental methods [1, 3, 4] have required detailed models of the interaction of Ps with matter and fields, that ultimately limit the possible precision. Here we investigate an alternative technique, wherein an energetic o-Ps beam produced via positron-gas collisions in a gas cell [5, 6] is allowed to decay in free-space. The surviving fraction is determined for various flight times using an adjustable micro-channel plate detector. Initial results are presented and improvements required to achieve competitive precision are discussed.

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**Poster Session / 11**

# Positronium spectroscopy with a beam of excited-state atoms

**Author:** Donovan Newson[None]

**Corresponding Author:** donovan.newson.18@ucl.ac.uk

Precision measurements of simple atomic systems [1] can be used to test fundamental theories and place constraints on physics beyond the standard model. Positronium is one such system and an attractive candidate as it is described to high-precision by bound-state quantum electrodynamics (QED) [2]. If one assumes QED is accurate in its current form, determination of lifetimes and intervals in positronium can constrain physics not included in the theory. Despite such promise, only a few properties of positronium have been determined precisely [3,4,5]. Application of instrumentation and techniques (e.g. [6]), novel to positronium, are required to at least match current theoretical uncertainties. In this work I describe the characterisation of an energetic beam of excited-state positronium atoms [7], towards precision microwave spectroscopy of the n=2 fine-structure using the method of separated fields [8]. Results of initial spectroscopic studies and recent progress are presented.

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**Poster Session / 18**

# A scheme for testing antimatter gravity with positronium using Rydberg atom interferometry

**Authors:** David B Cassidy[None]; Louise McCaul[1]; Stephen Hogan[None]

[1] *UCL*

**Corresponding Authors:** d.cassidy@ucl.ac.uk, s.hogan@ucl.ac.uk, louise.mccaul.21@ucl.ac.uk

Measurements of the acceleration due to Earth's gravity of positronium (Ps) atoms complement tests of antimatter gravity with antihydrogen at CERN [1], and extend tests of the Weak Equivalent Principle to purely leptonic systems. In its ground state, the annihilation lifetime of Ps of 142ns precludes precise measurements of g. However, when excited to Rydberg states annihilation is suppressed and such excited atoms can have lifetimes of >10µs [2]. These extended lifetimes can be exploited to perform interferometric measurements of g using a scheme we have developed, which is an electric analogue of Stern-Gerlach interferometry [3]. This is implemented by preparing the atoms in superpositions of Rydberg states with different static electric dipole moments, and using inhomogeneous electric fields to exert state dependent forces on them [4]. We will present the scheme and design of a full loop Rydberg-atom interferometer of this kind to be implemented to measure g for helium, and which can subsequently be extended to experiments with Ps.

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**Material Science / 6**

# Laser-driven positrons sources for Positron Annihilation Lifetime Spectroscopy

**Author:** Temour Foster[1]

[1] *Queen's University Belfast*

**Corresponding Author:** tfoster06@qub.ac.uk

Positron Annihilation Lifetime Spectroscopy (PALS) is one of the most effective material analysis techniques at detecting sub-nanometer defects in materials. Current conventional PALS facilities use positron beams of low keV energies and long durations, resulting in poor penetration depth and durations similar to the annihilation lifetime (~150ps), therefore giving poor resolution. By using laser-driven positrons, tuneable MeV-scale energies can be attained with short durations (~30ps), improving both the resolution and allowing for volumetric studies. Here, preliminary experimental results using taranis at QUB will be shown, along with an outline of future investigations at alfa

**Material Science / 8**

# Detection and Identification of Vacancy Defects in Antimony Selenide

**Authors:** Andreas Wagner[1]; Aryaveer Singh[2]; Jon Major[3]; Julia Wiktor[4]; Ken Durose[3]; Maciej Liedke[1]; Marcel Dickmann[5]; Theo Hobson[3]; Tom Shalvey[3]; Werner Egger[5]

[1] *Helmholtz-Zentrum Dresden - Rossendorf*

[2] *University of Dundee*

[3] *University of Liverpool*

[4] *Chalmers University of Technology*

[5] *Universität der Bundeswehr München*

**Corresponding Authors:** d.j.keeble@dundee.ac.uk, 2513724@dundee.ac.uk

Antimony selenide ($Sb_2Se_3$) is photovoltaic material with an optimal bandgap and a high optical absorption coefficient comprising of earth abundant elements. Solar cell power conversion efficiencies initially increased markedly but more recently the rate of increase has slowed. There is a large open circuit voltage consistent with the presence of detrimental concentrations of point defects. Here we report the results of variable energy positron annihilation lifetime measurements and related two component density functional theory calculations of positron lifetimes. Measurements have been performed on single crystal and thin film samples exhibiting p-type, intrinsic and n-type conductivity. The results provide evidence for the presence of both monovacancy and divacancy defects. They are consistent with both the Se and the Sb vacancies exhibiting negative charges states in intrinsic and n-type samples.

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# Vacancy defect identification in lead halide perovskite materials

**Author:** Aryaveer Singh[1]

**Co-authors:** Julia Wiktor [2]; Mingze Li [3]; Zhifang Shi [3]; Maciej Oskar Liedke [4]; Andreas Wagner [4]; Thi Hue Nguyen [5]; Michael Saliba [5]; Jinsong Huang [3]; David J. Keeble [1]

[1] *Physics, SUPA, School of Science and Engineering, University of Dundee, Dundee DD1 4HN, United Kingdom*

[2] *Department of Physics, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden*

[3] *Department of Applied Physical Sciences, University of North Carolina, Chapel Hill NC 27515 USA*

[4] *Institute of Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany*

[5] *Institut für Photovoltaik, Universität Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany*

**Corresponding Authors:** a.wagner@hzdr.de, 2513724@dundee.ac.uk, julia.wiktor@chalmers.se, jhuang@unc.edu, zshi@unc.edu, d.j.keeble@dundee.ac.uk, thi-hue.nguyen@ipv.uni-stuttgart.de, mingzeli@email.unc.edu, m.liedke@hzdr.de, michael.saliba@ipv.uni-stuttgart.de

There is intensive focus on the development of lead halide perovskite for a range of photonic devices including solar cells and gamma-ray detectors. Lead occupies the perovskite B-site where it is octahedrally coordinated by halide anions, while the larger A-site accommodates a small organic molecular ion, for example, methylammonium (MA) ($CH_3NH_3{}^+$). The rapid development has, in part, been attributed to reports of modest defect densities, there is nevertheless intense efforts to identify and quantify point defects in these materials. The Vacancy defects are a centrally important class hence positron annihilation spectroscopies are of directly relevance. Here we report the results of variable energy positron annihilation lifetime spectroscopy measurements performed on a range of lead halide perovskites using the mono-energetic positron source beamline at Helmholtz–Zentrum Dresden–Rossendorf. Measurements have been performed on single crystal $MAPbI_3$, $MAPbBr_3$, $MAPbCl_3$, and on formamidinium (FA) lead bromide, $FAPbBr_3$. Comparison with two-component density functional theory calculated lifetime for positron states localised at vacancy defects provide evidence for the identification of both Pb vacancy and MA-vacancies.

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# Neural Network Variational Monte Carlo for Positronic Chemistry

**Author:** Gino Cassella[1]

**Co-author:** Matthew Foulkes [1]

[1] *Imperial College*

**Corresponding Authors:** g.cassella20@imperial.ac.uk, wmc.foulkes@imperial.ac.uk

In recent years, several authors have demonstrated that deep neural networks can produce excellent representations of the many-body wavefunction for use in variational Monte Carlo calculations of the ground-state properties of atoms, small molecules, and simple solids. In this talk, I will briefly introduce the principle of neural network variational Monte Carlo, and discuss how it is quite straightforward to extend the neural network wavefunction to the description of multi-component (positrons and electrons) wavefunctions. I will share our initial, quite promising, results for the positron binding energy and annihilation rate of several well-studied molecules, and discuss why NNVMC may be particularly well suited for this problem.

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## Similarities in the Elastic and Ps Formation Differential Cross Sections for $e^+$-H and $e^+$-He

**Author:** Peter Van Reeth[None]

**Corresponding Author:** p.reeth@ucl.ac.uk

The elastic scattering differential cross sections (EDCS) for $e^+$-H and $e^+$-He below the first excitation threshold of the target are found to be very similar. They are evaluated using the Kohn variational method and both the individual partial wave contributions and their sum are very well converged. In both cases the EDCS below the Ps formation threshold, i.e. for pure elastic scattering, has a minima valley feature in which a significant minimum close to 90 degrees is found at $\approx$ 2.8 eV for H and $\approx$ 2 eV for He. These minima are shown not be vortices but to be related to the vortices found in the Ps formation differential cross sections just above the Ps formation threshold [1, 2]. We show that the valley type structure in the EDCS goes smoothly through the Ps formation threshold, linking up with a similar valley structure in both the EDCS above the threshold and the Ps formation DCS in which vortices have been found [1, 2].

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