

Antimatter

Every type of charged particle in nature has a corresponding antimatter partner with the same mass and opposite charge. Positrons (e^+) are the antiparticles of electrons (e^-) and thus a fundamental ingredient to the make-up of antimatter. The apparent imbalance between matter and antimatter in our universe remains one of the major unanswered questions in physics and cosmology.

In condensed matter, positrons annihilate with electrons within less than a billionth of a second. Prior to this, however, e^- and e^+ may combine to form the lightest-known atom positronium (Ps), sometimes referred to as an isotope of hydrogen (H), with the positron replacing the proton. In addition to their fundamental importance for the comprehension of the physical universe, the relevance of positrons and Ps to our everyday world encompasses materials science (as in the characterization of electronic and structural properties of industrially important materials) and medical applications such as Positron Emission Tomography (PET).

Topics of research in atomic and molecular physics with positrons vigorously pursued worldwide include positron-induced ion production (comprising ionization with and without Ps formation, annihilation), positron impact excitation (vibrational and electronic), Ps scattering, antihydrogen, and many-positron physics such as Ps_2 , Ps Bose-Einstein condensates and possible gamma-ray lasers.

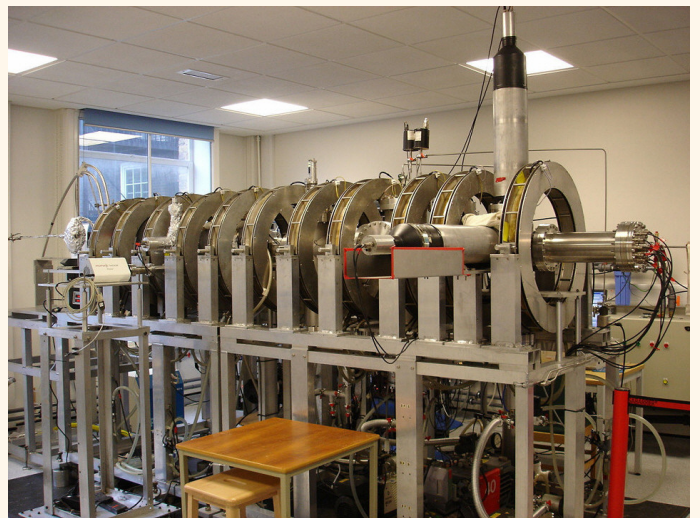
Except for self-annihilation, Ps is a very stable atom and its intrinsic lifetime ($\sim 10^{-10}$ - 10^{-7} s) is relatively long compared with typical times on an atomic scale (e.g. the orbital period of an electron in atomic hydrogen is $\sim 10^{-16}$ s). The understanding of processes leading to the formation and dissociation of positronium are important for the detailed description of how positrons react in matter—even in living tissue! At University College London, these unusual atoms are routinely produced as projectiles and their interactions with ordinary matter probed in a controlled manner.

If positrons come into contact with antiprotons, they may form antihydrogen, the first element in the antimatter periodic table. Antihydrogen is nowadays routinely produced at CERN and efforts are underway to trap it in order to examine it closely and measure its intrinsic properties (e.g. is the light emitted by excited anti-H the same as from H?) and its interactions with our world (e.g. does it fall in our gravitational field?).

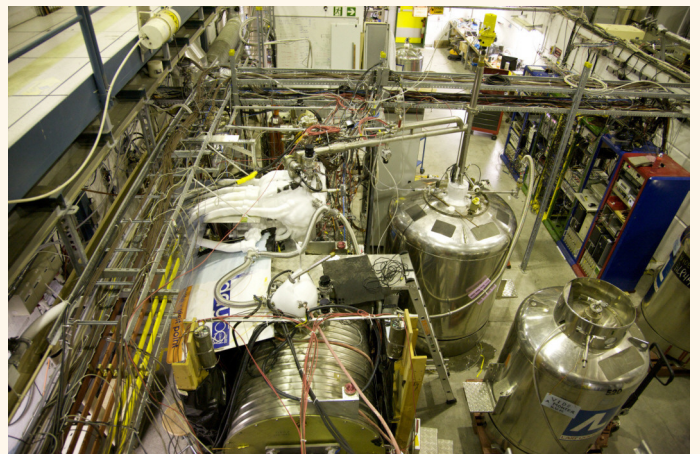
Trap-based positron beams, crucial in achieving the synthesis of molecular positronium (Ps_2) and antihydrogen, have enabled studies of positron-impact (vibrational and electronic) excitations as well as annihilation with an unprecedented energy resolution (~ 20 meV). The motivation for all these studies, together with concomitant theoretical advances, include the understanding of basic matter-antimatter interactions,



Positron Emission Tomography (PET) scanner (GE Healthcare).



The positronium beam at University College London—the only in the world (<http://www.ucl.ac.uk/positron-physics/>)!



The ALPHA apparatus for antihydrogen production at CERN (<http://alpha.web.cern.ch/alpha/>).

the provision of input in the analysis of astrophysical events and the development of positron-track simulations for accurate PET dosimetry.

Calculations involving antimatter are often more challenging than those involving only "normal" matter. For example, due to the electron-positron attraction, the systems containing positrons are characterised by stronger correlation effects than all electron systems. Understanding antimatter thus stimulates the development of new theoretical methods. The question of matter-antimatter asymmetry in the universe is a persistent source of discussion, and the cover of the October 2009 CERN Courier features the AMS Spectrometer, which will be on the International Space Station in 2010 and will search among other things for antimatter in the universe.

Positron annihilation spectroscopies are widely used to characterise the structural, chemical and electronic properties of materials on the atomic scale—both in the bulk and, by using positron beams, at surfaces and in thin layers or films. Fundamental studies have included the measurement of electron momentum distributions in solids, while the propensity for positrons to trap in open-volume point defects has proved very useful in the characterisation of technologically important materials. Positrons can provide information on structural changes associated with phase transitions, precipitation and deformation, and can act as 'magic bullets' in the study of embedded nanoparticles. Ps is used as a probe of open volume in polymers and of pores in thin low-k dielectric layers grown for nanoelectronics applications.

The development of positron microscopy will allow the performance of the spectroscopies summarised above with two- and possibly three-dimensional resolution. In the field commonly known as positron or Ps chemistry the formation of Ps in liquids, its enhancement and inhibition, electron and positron scavenging reactions, the formation of positron and Ps bound states, Ps trapping in 'bubbles' in liquids, Ps oxidation and spin conversion, have been studied experimentally. In surface science positron-annihilation-induced Auger electron spectroscopy (PAES) and low-energy positron diffraction (LEPD) have both proven to be extremely effective, both having advantages over their conventional electron counterparts.

Literature

Popular book:

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Popular articles:

Amanda Gefter: *The five greatest mysteries of antimatter*, New Scientist 22 April 2009

Philip Ball: *Matter-antimatter molecules made*, Nature online, <http://www.nature.com/news/2007/070910/full/news070910-5.html>

AMS gets its slot on a space shuttle in 2010, Cern Courier October 2009

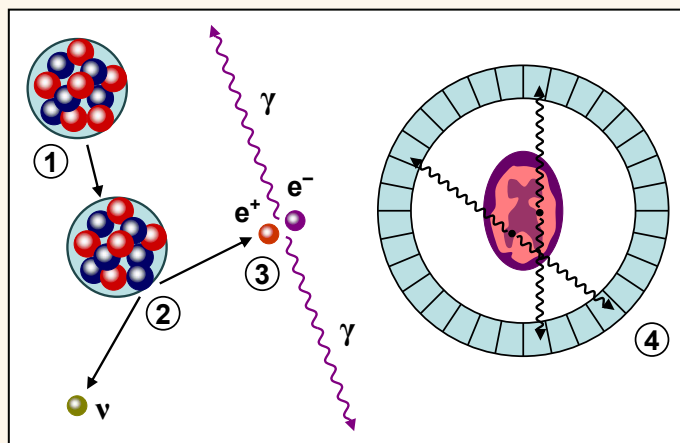
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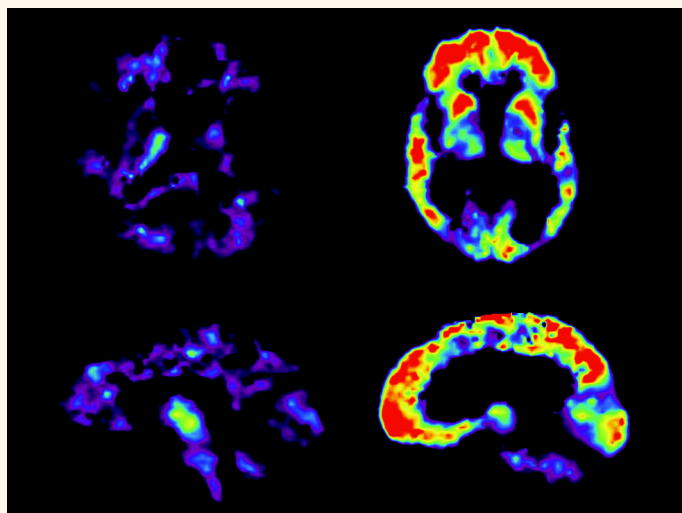
Paul G. Coleman: *Positron beams and their applications*, World Scientific Publishing Co. 2000

Recent reviews:

P. G. Coleman: *Positron Spectroscopy*, in *The Encyclopedia of Applied Spectroscopy*, ed. David L. Andrews, Wiley 2009



The principle of method of a PET scanner. A positron-emitting radionuclide (tracer) such as ^{11}C is introduced on a biologically active molecule into the body of the patient. Radioactive ^{11}C nuclei (1) decay by emission of a neutrino and a positron (2), which annihilates with an electron to produce two γ -rays of 511 keV each (3). In a PET scanner (4) the patient is surrounded by a ring of stationary detectors, which detect the γ -rays produced by e^+e^- annihilation, and from which a three-dimensional image of functional processes in the body can be reconstructed.



PET scans of the human brain of a cognitively healthy person and a person suffering from Alzheimer's Disease (Alzheimer's Disease Education and Referral Center, USA).

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