MSE 310 Lecture 19

Positron annihilation spectroscopy

Positron, also called **positive electron**, positively charged subatomic particle having the same mass and magnitude of charge as the electron and constituting the antiparticle of a negative electron. **Positron annihilation spectroscopy** (PAS) is a non-destructive **spectroscopy** technique that allows studying a variety of phenomena and material properties on an atomic scale. PAS measures the elapsed time between the implantation of the **positron** into the material and the emission of **annihilation** radiation.

When an **electron and a positron** collide, they **annihilate** resulting in the complete conversion of their rest mass to pure energy (according to the $E=mc^2$ formula) in the form of two oppositely directed 0.511 MeV gamma rays (photons). The total amount of **energy released** when a **positron** and an **electron annihilate** is 1.022 MeV, corresponding to the combined rest mass energies of the **positron** and **electron**. The **energy** is **released** in the form of photons. The number of photons depends on exactly how the **positron** and **electron annihilate**. **The positron** that is formed quickly disappears by reconversion into photons in **the** process of annihilation with another electron in matter.

Principle: The technique operates on the principle that a positron or positronium will annihilate through interaction with electrons. This annihilation releases gamma rays that can be detected; the time between emission of positrons from a radioactive source and detection of gamma rays due to annihilation corresponds to the lifetime of positron or positronium.

Interaction with Solids

When positrons are injected into a solid body, they interact in some manner with the electrons in that species. For solids containing free electrons (such as metals or semiconductors), the implanted positrons annihilate rapidly unless voids such as vacancy defects are present. If voids are available, positrons will reside in them and annihilate less rapidly than in the bulk of the material, on time scales up to ~1 ns. For insulators such as polymers or zeolites, implanted positrons interact with electrons in the material to form positronium.

States of Positron

Positronium is a metastable hydrogen-like bound state of an electron and a positron which can exist in two spin states. Para-positonium, p-Ps, (the positron and electron spins are anti-parallel) is a singlet state with a characteristic self-annihilation lifetime of 125 ps in vacuum. Orthopositronium, o-Ps, is a triplet state (the positron and electron spins are parallel) with a characteristic self-annihilation lifetime of 142 ns in vacuum. The behavior of positrons in molecules or condensed matter is nontrivial due to the strong correlation between electrons and positrons. Even the simplest case, that of a single positron immersed in a homogeneous gas of electrons, has proved to be a significant challenge for theory. The positron attracts electrons to it, increasing the contact density and hence enhancing the annihilation rate.

Positron Annihilation Lifetime Spectrometer

Positron annihilation lifetime spectroscopy uses positrons to probe material defects/voids/free volume at the sub-nm scale. The general working principle is based on correlating the lifetime (dwelling time) of the injected positrons against the sample void size (longer lifetimes correspond to large void sizes). The table-top spectrometer has a time resolution of ~ 270 ps, and uses a ^{22}Na positron source sandwiched between two thin Kapton foils. The source is sandwiched between the material of interest and the annihilation lifetimes and intensities are deconvoluted by fitting exponential decay functions using commercially available software.

Working

The experiment itself involves having a radioactive positron source (often ^{22}Na) situated near the analyte. Positrons are emitted near-simultaneously with gamma rays. These gamma rays are detected by a nearby scintillator and act as the "start" signal. The positrons interact with the analyte (either annihilating directly or forming positronium which subsequently annihilates) and on annihilation, gamma rays of lower energy than the start signal are emitted and detected as the "stop" signal. After enough correlated start and stop signals are detected (on the order of 1,000,000 such start/stop signals are required), average positron or positronium lifetimes can be fit to a histogram containing the frequency of individual lifetimes.

Applications

Positron annihilation spectroscopy (PAS) is a novel method that can provide molecular-level information about complex biological and macromolecular structure in a manner which is different, but complementary, to conventional medical and biochemical research methodology. And Capable of resolving voids in polymers, metals and semiconductors having a size range of less than a nm.