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Advancing material characterization through positron annihilation spectroscopy

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Abstract. *Positron annihilation spectroscopy has emerged as a robust technique for investigating the microstructure of condensed matter. This overview is tailored to users from diverse fields, offering insights into the method along with several illustrative applications.*
Key words*: positron-electron annihilation, positron lifetime, coincidence doppler broadening.*

Introduction

The positron annihilation spectroscopy (PAS) is a technique that uses positrons, the antiparticles of electrons, to study materials [1, 2]. When positrons encounter electrons in a material, they annihilate, releasing gamma-ray photons. By analyzing the characteristics of these photons, such as their energy and angular distribution, PAS provides information about the material's structure and defects. The fundamental concept behind utilizing positrons for defect detection is based on their sensitivity to changes in electron density caused by defects in materials.

When positrons encounter defects like vacancies or dislocations, the probability of annihilation with electrons varies, altering the characteristics of the emitted gamma-ray photons. By detecting and analyzing these changes, PAS can identify and characterize defects in materials, offering insights into their properties and structural integrity. The fundamental concept behind utilizing positrons for defect detection in techniques such as Doppler broadening spectroscopy (DBS), Coincidence Doppler broadening (CDB) spectroscopy, and positron annihilation lifetime spectroscopy (PALS) lies in the sensitivity of positrons to changes in electron density within material.

Research methods

Usage of positron annihilation spectroscopy (PAS) included both positron lifetime spectroscopy (PLS) and broadened Doppler spectroscopy (DBS) techniques. Positrons were generated either through radioisotopes or using a positron beam and injected into the subjects under investigation. PLS has been used to measure the lifetime of positrons before annihilation, providing information on the types of defects and densities within materials.

In addition, DBS allowed us to analyze the momentum distribution of electrons, yielding insight into the electronic structure of materials. By combining these techniques, we have gained a comprehensive understanding of the structural and properties of materials at the atomic level.

Results

The application of advanced PAS techniques has led to numerous exciting discoveries in materials science. For example, researchers have used PAS to study defects in semiconductors, including vacancies, dislocations, and dopant atoms. By understanding the behavior of these defects, scientists can optimize the performance of semiconductor devices such as transistors and solar cells. PAS can identify and characterize various types of defects in materials, including vacancies, dislocations, and point defects. In materials used in nuclear reactors, such as structural materials (e.g., stainless steel) and fuel cladding materials (e.g., zirconium alloys), defects can significantly affect mechanical properties, corrosion resistance, and irradiation behavior. PAS provides valuable information about the nature and distribution of defects, aiding in the assessment of material integrity and performance under irradiation conditions.

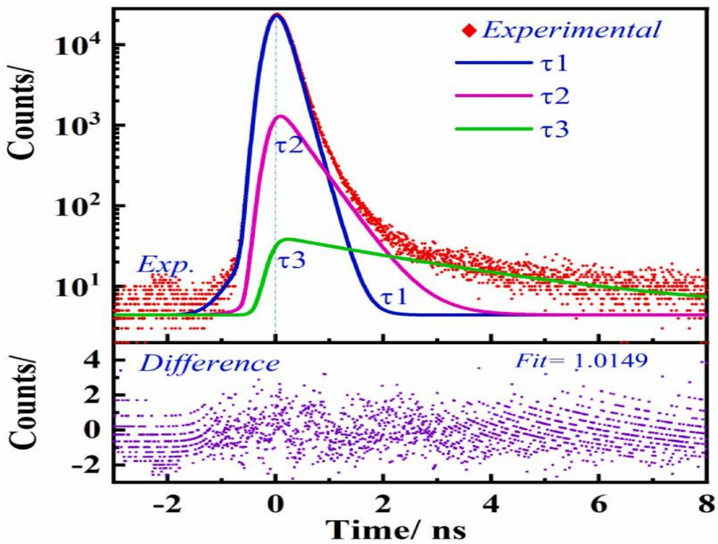

Fig. 1. An example of measured lifetime spectrum of $Y_3Al_5O_{12}$.
The graph displays the experimental data and the fitted lifetime components τ_1, τ_2, τ_3

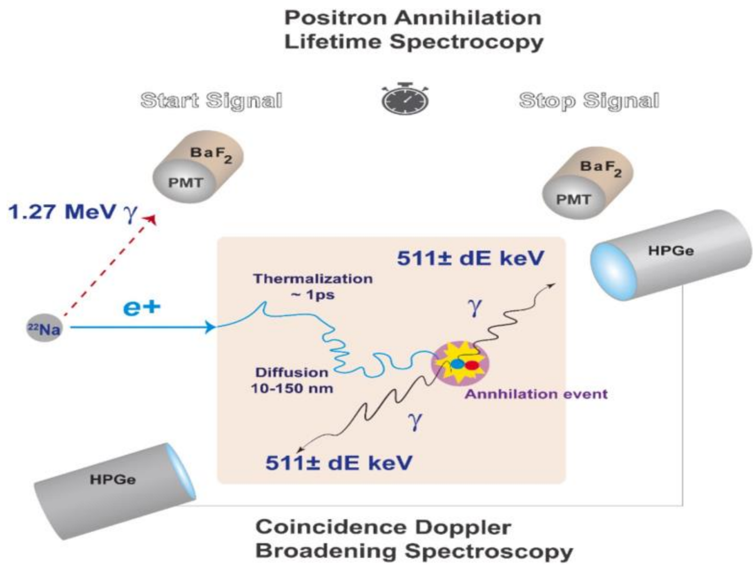

Fig .2. A schematic representation of PAS indicating basis of bulk PALS and CDB measurement

Conclusion

PAS has proven to be an effective method for studying the microstructures of condensed materials. It can explore microstructure details on an atomic scale, such as electrical structure and small-sized flaws. The primary advantages of PAS include its ability to detect minute flaws at low concentrations that are difficult to analyze using traditional techniques like TEM or X-ray diffraction. Additionally, PAS can test bulk characteristics near-surface regions, and layered structures.

Table 1

Comparison of positron annihilation techniques

Parameter	Standard PAS using radioactive sources	Slow positrons and variable energy positron beams	γ-Induced positron spectroscopy (GiPS) or accelerator-based PAS
Positron Source	Utilizes radioactive isotopes like Na-22.	Generated from radioactive decay, pair production from high-energy γ-rays, or nuclear reactions.	Positrons generated directly within the sample by pair production from high-energy γ-rays.
Positron Energy	Fixed energy, generally several hundred Kev up to 1 MeV.	Tunable energy from 0 to 30 keV, suitable for depth-resolved investigations	Determined by the energy of incident γ-rays. Spatial Resolution: Highly penetrating probe up to a centimeter of depth with atomic resolution.
Spatial Resolution	Limited, suitable For bulk defect measurements within a few hundred microns.	Provides depth-resolved probing from surface to approximately 1 μm in solids.	Suitable for bulk measurements, highly sensitive to open volume defects and dislocations. Valuable for assessing damage in structural materials, particularly in nuclear reactors.
Applications	Suitable for bulk defect studies but not for depth-resolved or surface investigations.	Ideal for surface studies, thin films, interfaces, and defects induced by ion irradiation. Suitable for both Doppler broadening spectroscopy (DBS) and positron annihilation lifetime spectroscopy (PALS).	Suitable for bulk measurements, highly sensitive to open volume defects and dislocations. Valuable for assessing damage in structural materials, particularly in nuclear reactors.

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