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APPLICATION OF THE POSITRON ANNIHILATION TECHNIQUE

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ABSTRACT

The principles of positron annihilation and four positron experimental techniques are described. The application of positron annihilation technique in material science, atomic physics and other related fields are discussed.

Key words: Positron annihilation technique Material science Atomic physics Live science Positron astrophysics Positron emission tomography

I. INTRODUCTION

Positrons can be used as very sencitive microprobes of the physical properties of the matter. In conventional positron annihilation technique (PAT) experiments, fast positrons from a long-lived radioactive source such as ^{22}Na or ^{58}Co are injected into the condensed sample. The positrons lose their energy by ionizing collisions and phonon scattering and reach thermal equilibrium with the sample in a few picoseconds penetrating the sample well into the bulk with mean depths of 10—100 μ m. In defect-free mono-crystals the positrons are repelled by the positive ions and having maximum in the interstitial regions between the atoms. Being the antiparticle of the electron, each positron annihilates with an electron of the matter, emitting two or three annihilation quanta with a characteristic annihilation rate (inverse lifetime) that depends on the electron density it overlaps with positron. Typical annihilation lifetimes in solid are a few hundred picoseconds. Prior to annihilation, the positrons can be trapped in low density regions of the sample, such as a vacancy, a dislocation and microvoids, etc.

Three experimental techniques have been dominating in PAT, Viz. the lifetime, the angular correlation and the Doppler broadening techniques. They are all based on nuclear spectroscopy by which the emitted gamma quanta are detected. For example, the positron annihilation lifetime can be obtained accurately by measuring with fast coincident techniques the time interval distribution between the nuclear 1.28 MeV γ, which follows promptly the emission of a positron from ^{22}Na, and one of the annihilation γ-rays. More detailed description of these experimental techniques may be found in Ref[3]. In recent years, the slow positron beam with variable energy has been developed for surface and atomic physics. The principle of such a beam is sketched in Fig.1. Positrons from a radioactive source (here ^{58}Co) are injected into a single crystal metal moderator (Instead of a radioactive isotope as the source, positrons can also be produced through pair-creation by the bremsstrahlumg generated when high energy electrons from a accelerator hit a target). In the moderator the positrons slow down, and a few of them thermalize so close to the surface that they may diffuse back to it before they annihilate. Having reached the surface, the positrons have a certain probability of being re-emitted. The monoenergetic beam of positrons can then be accelerated to the desired energy and injected into the sample.

Positron annihilation research is a very wide field as can be seen from the proceedings of the recent international conference[5] and other recent books[6]. In this review, attention will be given to the positron studies of material science and atomic physics, etc.

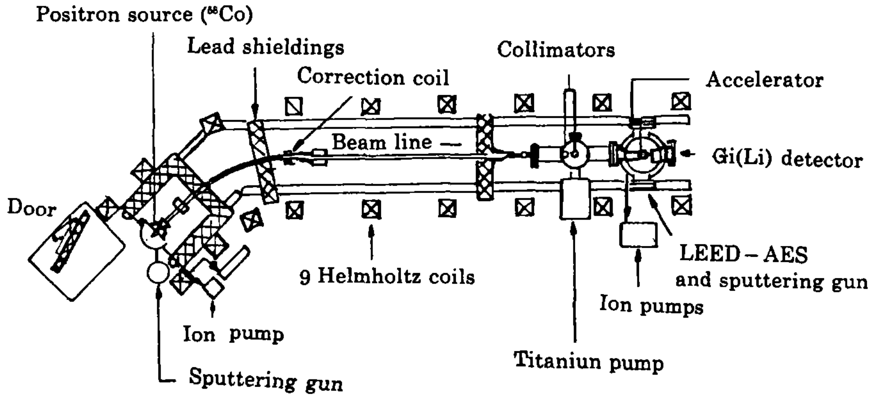


Fig.1 Diagram of a typical slow positron beam

Ⅱ. MATERIAL SCIENCE

In material science. the PAT has been successfully applied to study the defects, phase transition and electronic structure over past two decades. The typical problems include vacancy formation and migration, vacancy-impurity interaction, plastic deformation, fatingue and creep, radiation damage, martensitic transformation, various quenching and annealing processes, presipitation, etc.

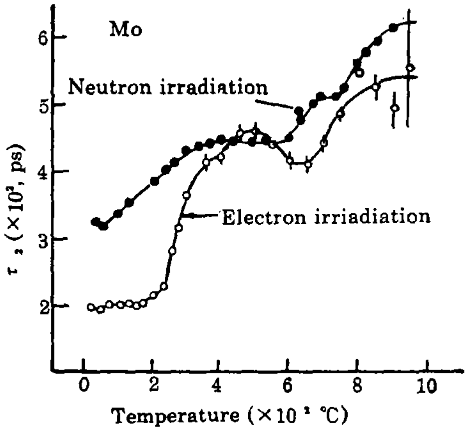
As well-known, the defect studies in material science are usually analyzed by the so-called trapping model to extract some quantitative information. For example the changes in the lifetimes and intensities can be detected for relative vacancy concentration as low as 10^{-6}-10^{-7}. For vacancy clusters, the concentrations of large voids can be detected which are 2-3 orders of magnitude lower than for vacancies. In vacancy studies, one can obtain the formation energy of monovacancy directly from an arrhenius plot of the proper combination of measured parameters. These measurements yield the most precise or the only values of the vacancy formation energy for many metals. Some of the values are listed in table 1 and compared with results from quenching studies.

Table 1

Vacancy formation energies (eV)[4]

Metal	PAT	Quenching
Al	0.66	0.66
Ag	1.11	1.10
Au	0.97	0.94
Cu	1.31	1.30
Ni	1.8	1.6
Mo	3.0	3.2
W	4.0	3.6

Examples of the application of PAT to the investigation of the vacancy clustering in electron and neutron irradiated Mo are shown in Fig.2[1]. The defect-trapped positron lifetime τ_2 is seen to vary continuously with annealing in the electron-irradiated sample from that value (220ps) representative of monovacancies in Mo to about 450ps, which is representative of well defined voids in this material.



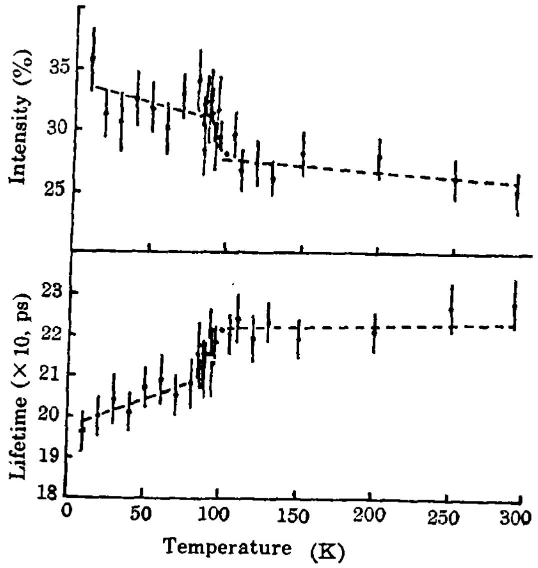


Fig.2 τ_2 vs annealing temperature in the irradiated Mo

Fig.3 Positron parameters vs temperature in Y-Ba-Cu-O

The voids observed by PAT were confirmed by means of TEM. The voids observed by TEM were about 3 nm in diameter and at a density of about 1—5× 10^{13} voids cm^{-3}, close to the limits of both the resolution and sampling capabilities of conventional TEM. The initial value of τ_2 in neutron-irradiated case is considerably higher

($>$300ps), indicating the void-like nature of depleted zones present in this case.

The sensitivity of the PAT to the high-*Tc* superconductors has recently been shown by several experiments[7]. Fig.3 shows the results of positron annihilation parameters for Y-Ba-Cu-O system. The observed positron lifetime and Doppler broadening *S* parameter have an onset increase near the *Tc* (90K). This variation does not exist in a nonsuperconducting sample that contains a saturated oxygen vacancy. These results give evidence that oxygen vacancy and electronic structure change play an important role for high-*Tc* superconductivity.

Other examples of the investigations on physisorbed surface[8], amorphous alloys[5], magnetic alloys[5], molecular solids[9], etc. can be found elsewhere.

Ⅲ. ATOMIC PHYSICS [10]

The positron-electron pair can also form a quasi-stationary state called positronium (Ps). Apart from the effects due to annihilation, Ps is an analogue of the hydrogen atom generallly not formed in metals, but is found in metal oxides, molecular solids, liquids and gases. Owing to the development of slow positron beam, the positron scattering cross sections and new results of Ps physics have been measured.

One of the first uses of slow positrons was the study of the positron-He total scattering cross section. The results provide a sensitive test of approximate theories which have been developed for electron scattering. A particularly sensitive region occurs for a few eV positron energies where a minimun in the total cross section has been observed. Recent measurements of the differential scattering cross section for positrons in Ar have been completed. In these experiments, the positron energy is below the inelastic threshold so that the energy of the positrons after scattering is the same as before. At higher energies the inelastic contributions to the total cross section are observed separately. In addition to having an interesting Ps formation channel, positron inelastic scattering is of interest because the absence of exchange interactions suppressed the excitation of triplet states.

As mentioned above, Ps is a two-body, particle-antiparticle and leptonic system. The Ps parameters of interest for QED tests are the energy level and the annihilation rate of the low lying states. The energy separation between the singlet (p-Ps) and triplet (o-Ps) levels of the Ps ground state ($n=1$) has been measured. The reported results are agreed with the theoretical value at 5ppm. The Lyman-α photons of Ps were derectly observed by using slow positrons thus ending a twenty-five-year search for the $n=2$ states of Ps. The result of first Ps fine structure measurement, $\triangle\gamma$ ($2\ {}^3S_1 - 2\ {}^3P_2$), is 8628.4$\pm$6.6 MHz and theoretical value is 8625 MHz plus several MHz. Using the same techniques as above, the high precision o-Ps($n-1$) annihilation rate value $\lambda = 7.050 \times 10^6\ s^{-1}$ has been obtained which then led to a theoretical reevaluation of this rate.

IV. OTHER RALATED FIELDS [11]

1) Positron astrophysics

A number of oberservations of γ -rays of astrophysical origin have been made. Discoveries of lines at 0.5 MeV associated with a solar flare and the galactic center have been made using ballon-borne NaI or Ge (Li) detectors. The line from the galactic center is thought to originate from direct annihilation and Ps formation by positrons on interstellar hydrogen, although identification of the 3γ continue radiation is marginal. The narrow width (*FWHM* < 3.2keV) of the galactic center line has been shown to suggest that the interstellar medium temperature is <10 K and degree of ionization is 75% . Perhaps the most spectacular gamma-event observed so far was that nine spacecraft simultaneously (on 5 march 1979) observed a gamma burst at 0.38 MeV from the direction of large Megellinic cloud. The source is proposed to be a vibrating neutron star, whose gravitation red-shifts the 0.511 MeV line due to direct annihilation and Ps formation.

2) Live science

Origin of biological activity can be studied by the polarized positron beam with probing the possible connection between the helicity of beta electrons emitted by natural radionuclides and the L-amino acids in living organisms. In dissymmetric molecules the spin-orbit interaction will produce a helicity in the bound molecular electrons which leads to an asymmetry in ionization by polarized electrons. For the electrons from the radioactive decay, the effect is reduced by a factor of 10^5 compared to ionization by electrons, producing a small, but constant asymmetry in the destruction of one isomer. This slight preference could, through biochemical amplification mechanisms, lead to the present dominance of L-amino acid in biological organisms. Bound electron helicity density also gives rise to an asymmetry in *o*-Ps formation by helicitized positrons without the factor of 10^5 loss in sensitivity. The positron of 400 eV formed *o*-Ps in the crystal of amino acids crystine. The asymmetry upon reversal of positron helicity or isomer (L to D) was found to be under 3×10^{-4} for it, a factor of 10^3 larger than expected from theory.

3) Positron emmission tomography(PET)

PET is a new important technique in medical physics. The medical information obtainable with PET is not to be confused with that of XCT which produces density maps of the body. PET makes possible "in situ" biochemical function studies, such as glucose uptake by the brain. With improved resolution it can become a tool of fundamental importance in basic medical sciences.

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