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Slow positron beam at the JINR, Dubna

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Abstract. The Low Energy Positron Toroidal Accumulator (LEPTA) at the Joint Institute for Nuclear Research (JINR) proposed for generation of positronium in flight has been adopted for positron annihilation spectroscopy (PAS). The positron injector generates continuous slow positron beam with positron energy range between 50 eV and 35 keV. The radioactive ^{22}Na isotope is used. In distinction to popular tungsten foil, here the solid neon is used as moderator. It allows to obtain the beam intensity of about 10^5 e^+/s width energy spectrum characterized by full width at half maximum (FWHM) of 3.4 eV and a tail to lower energies of about 30 eV. The paper covers the characteristic of variable energy positron beam at the LEPTA facility: parameters, the rule of moderation, scheme of injector, and transportation of positrons into the sample chamber. Recent status of the project and its development in the field of PAS is discussed. As an example, the measurement of the positron diffusion length in pure iron is demonstrated.

Key words: positron beam • positron injector

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Introduction

Positron annihilation spectroscopy (PAS) is a successful method for the detection of open-volume defects in solids. It allows to detect types of open-volume defect with the size lower than 10 nm and to approximate concentration on the level 10^{-7}. In the case of conventional PAS experiments, positrons emitted directly from an isotope are applied. They are characterized by continuous energy spectrum from 0 to some maximal energy specific for a given source, e.g. 545 keV for ^{22}Na. For this reason, the mean implantation depth is several dozen micrometers in metals and about 1 mm in polymers. Thus the bulk region of a sample is studied.

The application of PAS in studies of surfaces, thin films, or layered structures is possible using a slow positron beam. This device allows to implant monoenergetic positrons with energy between a few dozen electron-volts to a few dozen kiloelectron-volts into a sample. The opportunity of energy controllability allows to precise location on the given depth of up to several micrometers. In this way, the slow positron beam supplements conventional experiments. Recently, these types of devices have been appearing in the wider amount of laboratories.

In this paper, variable energy beam (VEP) at Low Energy Positron Toroidal Accumulator (LEPTA) facility at the Joint Institute for Nuclear Research (JINR) in Dubna is presented. In particular, its description, rule of working, and adjustable parameters in the current version are going to be discussed.

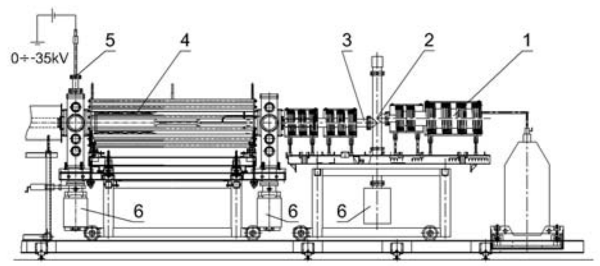

Fig. 1. The scheme of positron injector at the LEPTA facility: 1 – ^{22}Na positron source (+50 V); 2 – diaphragm; 3 – transfer channel; 4 – Surko trap; 5 – target insertion; 6 – vacuum pumps.

Additionally, apparatus used in PAS experiment as well as the nearest plans of development are given.

Positron injector

Positron injector used as VEP is a part of the LEPTA facility that has been realized since 2000 at the Dzhelepov Laboratory of Nuclear Problems, JINR in Dubna. The main goal of this project is generating a high-intensity positronium beam in flight [1].

The scheme of injector is presented in Fig. 1. Positrons emitted from ^{22}Na isotope with energy up to 0.545 MeV are moderated to a few electron-volts on the frozen neon. The capsule with ^{22}Na is situated inside the copper cylinder with a slot in the shape of a cone in front of an active surface. In front of this system, the ring with four nozzles is placed. Everything is protected by the ambient thermal screens. The liquid helium cools down the cylinder with the source to the temperature of 7 K, while the temperature around it equals 30 K. The neon gas is injected into the cone and creates the solid layer on the surface serving as a moderator. The rule of moderation and design of cryogenic source that is under potential of +50 V are

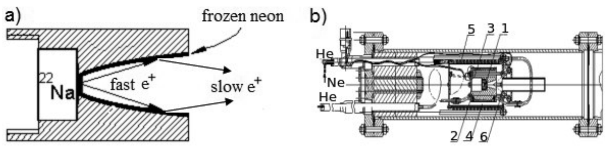

Fig. 2. Positron source: (a) the rule of moderation; (b) design of cryogenic source: 1 – copper subscribe with isotope ^{22}Na; 2 – copper cylinder; 3 – cryogenic heat exchanger of the copper cylinder; 4 – thermal shield; 5 – cryogenic heat exchanger of the thermal shield; 6 – nozzles.

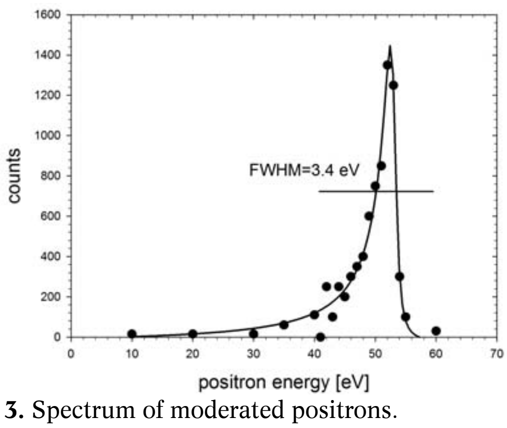

Fig. 3. Spectrum of moderated positrons.

Table 1. Parameters of slow positron beam at the LEPTA facility

Feature	Value
Activity of ^{22}Na isotope	~20 mCi
Moderator	frozen Ne (7 K)
Longitudinal magnetic field	100 Gauss
Vacuum conditions	10^{-9} Torr
Intensity	~10^5 e^+/s
Energy range	50 eV ÷ 35 keV
Diameter of the flux	5 mm

shown in Fig. 2. The spectrum of moderated positrons is presented in Fig. 3. The black circles represent the number of counts per 1 s for the given positron energy. The solid line is the best fit using Pearson type IV function. This is a nonsymmetrical distribution with a long tail from the low values of potential side. The maximum is located around 52 V and the full width at half maximum (FWHM) equals 3.4 V. The detail parameters of VEP are gathered in Table 1.

On the exit of the moderator, both fast and slow positrons appear. Next, they are separated by the combination of the longitudinal magnetic field and two sections of the transverse magnetic field of opposite direction placed one by one. As a result, the slow positrons have a 'slalom-like' trajectory when they come to the aperture diaphragm. Only low-energy positrons go to the sample chamber. The Surko trap [2] is off during PAS experiment. The chamber with samples is located about 2 m from the source, and positrons are guided in the longitudinal magnetic field strength of 100 Gauss. The holder with samples hung on a vertically moving rod is under potential, which can be changed in the range between 0 and –35 kV. In this way, positrons can be accelerated to expected energies. The positron current obtained in the device is about 10^5 e^+/s.

Example of PAS results

At the LEPTA facility, we measure Doppler broadening (DB) of annihilation line technique vs. the energy of injected positrons. Wider description of this method is reported, for example, in [3, 4]. The energy spectrum of gamma quanta emitted from annihilation process in a sample is registered by high-purity germanium (HPGe) detector. At the LEPTA, coaxial detector with 30% efficiency and FWHM = 1.2 keV for 511 keV energy resolution is used. The obtained annihilation line is next analyzed to calculate the so-called S parameter. It is defined as a ratio of area under the central part of annihilation line to the total area below the line. The energy window for calculation of S parameter is 511 ± 0.82 keV. In this case, the S parameter vs. positron incident energy is analyzed.

As an example, we demonstrate in Fig. 4 the measurement of S parameter dependency for pure iron. A sample of pure iron (99.8% purity delivered from Goodfellow) annealed for 2 h at 700°C in N_2 flow gas atmosphere and cooled down slowly to room temperature to remove manufactured defects. After

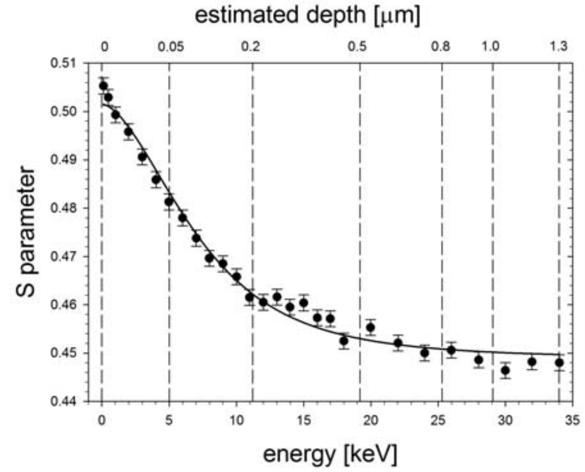

Fig. 4. The dependency of the S parameter on the incident positron energy for well-annealed iron. Solid black line represents the best fit of Eq. (3) with (1) and (2) to the experimental points.

annealing, samples were etched in the 25% solution on nitride acid in distilled water to clean the surface.

The S parameter decreases with energy and saturates for higher values. This dependency reflects the fact that implanted positrons after thermalization can diffuse during their random walk also to the entered surface and annihilate there. Usually, the surface is a large open-volume defect for which the S parameter is slightly larger than that in bulk in the interior. The detail solution of the diffusion equation for positrons allows to obtain the following equation for the dependency of the S parameter vs. the positron incident energy E [5]:

$$\text{(1)} \qquad S(E) = S_{\text{bulk}} + \frac{(S_{\text{surf}} - S_{\text{bulk}})}{1+\kappa^{-1}} \int_0^\infty dx\, p(x,E) \cdot \exp(-x/L_+)$$

where $\kappa = (\alpha/D_+)/L_+$, $L_+ = \sqrt{D_+/\lambda_{\text{bulk}}}$, and α is the positron absorption coefficient at the surface; D_+ is the positron diffusion coefficient; λ_{bulk} is the annihilation rate in bulk; and S_{bulk} and S_{surf} represent the corresponding values of the S parameter in the bulk and at the surface, respectively. The Makhovian function is commonly used as the positron implantation profile $p(x,E)$:

$$\text{(2)} \qquad p(x,E) = \frac{mx^{m-1}}{x_0^m} \exp\left[-\left(\frac{x}{x_0}\right)^m\right]$$

where: $x_0 = \frac{A_{1/2}}{\rho(\ln 2)^{1/m}} E^n$,

ρ represents the density of the implanted medium, and the values of other parameters, i.e., n, m, and $A_{1/2}$, one can find in [6], for iron are as follows: $m = 1.766$, $A_{1/2} = 2.39$ mg/(cm^2·keV^n), $n = 1.692$, $\rho = 7.87$ g/cm^3 describing positron implantation profile.

In slow positron beam experiments, certain amount of the so-called epithermal positrons can be expected. They energies are much higher than thermal energy, and they can annihilate close to or on the entrance surface. Commonly, the fraction of epithermal positrons that reach the surface as the function of energy is expressed as follows:

$$\text{(3)} \qquad J(E) = \int_0^\infty dxp(x,E)\exp(-x/L_{\text{epith}})$$

where L_{epith} is the scattering length parameter whose value is around few nanometers [7]. Then the measured profile of the S parameter can be expressed as follows:

$$\text{(4)} \qquad S'(E) = S(E)[1 - J(E)] + S_{\text{epith}} J(E),$$

where S_{epith} is the S parameter corresponding to the epithermal positrons trapped at the surface.

The best fit of Eq. (4) with (1) and (2) to the experimental points is depicted as a solid line in Fig. 4. The value of adjusted parameter were equal as follows: $S_{\text{bulk}} = 0.4480 \pm 0.0008$, $S_{\text{surf}} = 0.4976 \pm 0.0012$, $S_{\text{epith}} = 0.5064 \pm 0.0015$, and $L_+ = 131.3 \pm 9.7$ nm. Fitting we assumed that $L_{\text{epith}} = 1.5$ nm and $\kappa \to \infty$. The experimental data are well described by the equations.

We should emphasis the quite large value of the positron diffusion length L_+. Iwai *et al.* [8] achieved similar profile for sample of iron annealed for an hour. They did not fit them but the difference between approximated values of S parameter for surface and saturation are comparable. Similar agreement occurs in the case of investigations provided by He *et al.* [9]. In this case, authors fitted obtained profile using VEPFIT [10] getting $L_+ = 160 \pm 2$ nm. The difference between positron diffusion lengths can be connected with the ranges of implanted energies, which, in the case of He, was up to 25 keV. In this way, the saturation was not well marked and could have an impact on the fit. Positron diffusion lengths reported from nondefected metals are close to 100 nm [11]. Additionally, Lukáč *et al.* [12] obtained $L_+ = 142 \pm 2$ nm for defect-free iron. On the basis of the above analysis, the conclusion that VEP at the LEPTA facility along with a DB spectrometer gives correct results seems to be reasonable.

Plans for development

Recently, the sample chamber has been placed behind Surko trap [2]. This location is connected with some inconveniences related with longer time of vacuum creation as well as providing other experiments demanding injection of positrons to the LEPTA ring. For this reason, to separate PAS investigations, a new channel is under construction. Using rotating solenoid for the generation of magnetic field, positrons will be directed to the new sample chamber situated under 30° in the distance of 1.5 m from the main channel.

The next improvement concerns the installation of cryocooler RDK-408D2 with 1.0-W capacity for 4.2 K bought in SHI Cryogenics Group. In this way, experiments provided on VEP will be independent to the presence of liquid helium, which so far has limited the frequency of experiments, their time, and increased costs.

At the end of 2015, bringing of new positron source of ^{22}Na with activity 40 mCi from iThemba LABS is expected. It will allow to increase the intensity of slow positron beam and intensify the measurements.

Summary

VEP beam at the LEPTA facility has recently been applied in PAS investigations. It offers possibility of measurements with slow positrons in the energy range between 50 eV and 35 keV with energy resolution of 3.4 eV. The DB studies can be provided with high-quality HPGe detector with energy resolution of 1.2 keV at 511 keV. The test performed on the sample of well-annealed iron shows that apparatus available at the LEPTA generates correct results, which are in the good agreement with those presented in the literature. Existing apparatus is still being developed for more intensive and effective using in experiments.

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