# POSITRON ANNIHILATION SPECTROSCOPY AT LEPTA FACILITY

P. Horodek, A. Kobets, I. Meshkov, V. Pavlov, A. Rudakov, A. Sidorin, S. Yakovenko,
JINR, Dubna, Russia

*Abstract*

At the moment Positron Annihilation Spectroscopy (PAS) unit is being created as a part of LEPTA project at JINR in Dubna. A slow positron beam, dedicated to creating a positronium atom in flight, will also be used for material research related to detection of point defects under the surface. For this purpose Doppler broadening of annihilation line spectrometer is being made. Basis of the method, operational principle, plans and current state of works, are all presented in this article.

## INTRODUCTION

Positron Annihilation Spectroscopy method is sensitive to presence of defects in materials. Its currently highly developed measurement techniques enable detection of imperfection of crystal lattice the size of a lattice constant. Vacancies, concentrations of vacancies, pores and dislocations can be spotted in this way. Since late 1960s, when it was discovered that a positron interacts with defects, PAS method has been developing. At the moment it has got solid theoretical basis. A growing interest in this method in condensed matter research and materials engineering in recent years resulted not only in new results but also in a search for increasingly sophisticated measuring techniques. Research on monoenergetic positron beams and positron microscopy are the current trends in this department.

## POSITRONS IN THE MATTER

Positron, antiparticle of an electron, coming from $\beta^+$ decay in PAS experiments is implanted into the tested sample directly after emission from isotope or into a specially formed beam.

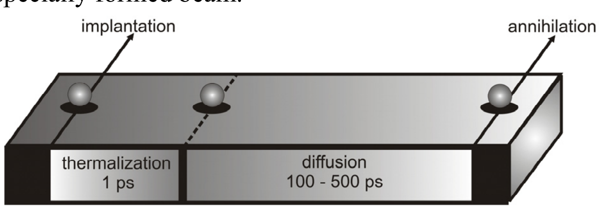


Figure 1: Stages of positron implantation into the matter.

As it possesses both energy and charge, it reacts elastically and non-elastically with ions and electrons, and to a lesser degree with phonons and impurities. Thus, after circa 1 ps it reduces its energy to thermal oscillation energy i.e. about 25 meV [1]. This stage is called thermalization. Next, anti-electron, which at this stage is in a state of thermodynamical balance with its environment starts free diffusion, which is a random walk over the area occupied by $10^7$ atoms. Such state lasts from 100 to 500 ps and it ends with an encounter with an electron. The process of annihilation into two gamma quanta of energies that equal about 511 keV occurs in over 99% cases [2].

Therefore, the process of positron-electron annihilation does not occur immediately after positron appears in the matter. The fact that in different stages (schematically marked in Fig.1) it spends a certain time in the material, is significant from PAS point of view.

In the central mass system annihilation quanta are emitted in the exactly opposite direction (see Fig. 2). In a laboratory system a certain deviation from this collinearity will be observed, expressed by

$$\Delta\theta = \frac{p_\perp}{mc} \quad (1),$$

where m is electron's mass, c is speed of light in a vacuum and $p_\perp$ is a perpendicular component of the momentum of the annihilating pair. A deviation from 180° will be bigger, the bigger momentums of a positron and an electron. The momentum additionally manifests itself in gamma quanta energies, which are changed as a result of Doppler effect

$$E_\gamma \cong mc^2 + E_B \pm \frac{p_{\parallel} c}{2} \quad (2)$$

where $E_b$ is the energy of positron-electron pair coupling and $p_{||}$ is a perpendicular component of the pair's momentum. It is worth emphasising that positron's momentum is negligibly small in relation to electron's momentum, therefore it usually omitted in deliberations.

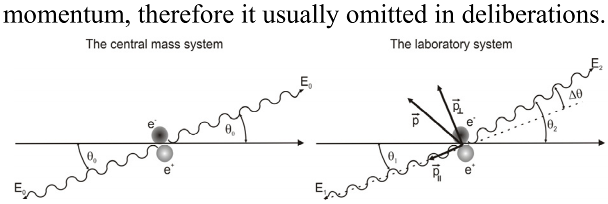


Figure 2: The annihilation processes in the two systems.

During its random walk a positron may encounter places which have a modified electron density. Those place are structural defects such as vacancies, inside of which a positron may be located. Electron density in such traps is smaller in comparison with the defect's environment. This inevitably is reflected in deviation from collinearity of annihilation quanta and in their energies, which are then respectively smaller, as well as in an average life time of a positron in a defect, which is longer than outside of it.

Observations of angular correlations of annihilation quanta, changes of energies or life times are operational basis of the three basic measuring PAS techniques. The technique of observation of Doppler broadening of annihilation gamma line is going to be more widely discussed further in the article.



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## THE DOPPLER BROADENING OF ANNIHILATION GAMMA LINE

Widely known in physics Doppler's phenomenon causes a change of energies of annihilation quanta according to the formula (2), which, having neglected electron's momentum and energy, can be thusly expressed

$$E_\gamma \cong mc^2 \pm \sqrt{\frac{1}{2}mc^2 E}\,. \qquad (3)$$

If the energy of an annihilating positron equals e.g. 7eV (Fermi energy for copper), then a change of energy of annihilating gamma quantum, according to the above formula, will equal 1,4 keV. Thus, the total broadening of annihilation line will equal 2,68 keV.

Observation of such broadening requires using detectors of a high energetic resolution. Currently available germanium detectors allow to take measurements with resolution equal to 1-2 keV around 511 keV energy.

Doppler broadening of annihilation line technique is used to detect concentrations of defects such as vacancies and their accumulations. A signal from annihilation of a trapped positron gives broadening of the 511 keV line accordingly smaller than the one that would occur in case of annihilation with nucleus electrons. In other words, less defected sample gives smaller broadening of the 511 keV line.

In practice, information about concentration of defects is received from analysis of the shape of annihilation line, by calculating two important parameters, called S and W. Exemplary annihilation line as well as the rule for calculating both parameters are presented in Fig. 3.

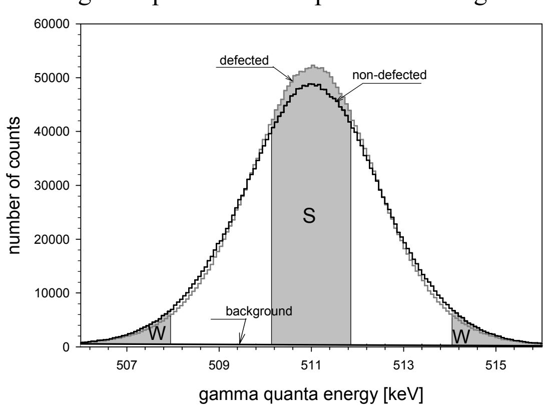


Figure 3: The annihilation lines with marked areas defining parameters S - and W - measured in stainless steel. The grey line comes from the defected (by sliding) sample, while the black line represents the non-defected sample.

S parameter defines proportion of annihilation of positrons with low-momentum electrons. It is closely related to concentration of defects in a material. It is defined as ratio of surface area under the central part of the 511 keV line to total surface area under this line. Areas are usually selected so that their ratio approximated 0,5. Bigger S parameter value means bigger concentration of defects.

The second parameter, the so called W parameter is defined as ratio of surface area under the wing part of 511 keV line to total surface area. It is related to annihilation of positrons with high-momentum electrons and it provides information about chemical environment of the defect. Value of this parameter is also selected arbitrarily – it tends to be smaller than 0.01.

Both parameters S and W are calculated after background reduction. Calculations are made by special computer software. As stated above, the analysis of results of Doppler broadening of annihilation line is based on calculating S and W parameters, changes of which provide information on changes in concentration of defects [3,4].

## PAS AT LEPTA PROJECT

Since 2000 at JINR in Dubna project LEPTA has been realised. Its main aim is to acquire a positronium atom in flight [5]. A positron beam constructed for this aim can also be used for PAS.

The concept of producing the beam is the following. Positrons emitted from $^{22}Na$ go through a moderator, which is condensed Ne source. As a result of elastic scatterings on gas particles some electrons lose their energy. Those two types of particles are separated by the use of perpendicular magnetic fields. Fast positrons are stopped at diaphragm, while the slow ones are slaloming and are then formed into a beam and accelerated by negative potential to needed energies. Currently available beam's parameters are given in Table 1.

Table 1: General Beam Parameters

| Feature | Value |
|---|---|
| activity of $^{22}Na$ isotope | 25mCi |
| moderator | frozen Ne (7K) under pressure $10^{-8}$ Torr |
| longitudinal magnetic field | 100 Gs |
| vacuum conditions | $10^{-6}$ Pa |
| intensity | $10^5$ $e^+$/s |
| energy range | 1 eV ÷ 50 keV |
| diameter of the flux | 5 mm |

Positrons are implanted from the beam into the sample which has electric current applied to it. Quantum 511 keV created through annihilation is registered by a DBGL spectrometer, which scheme is shown in Fig. 4.



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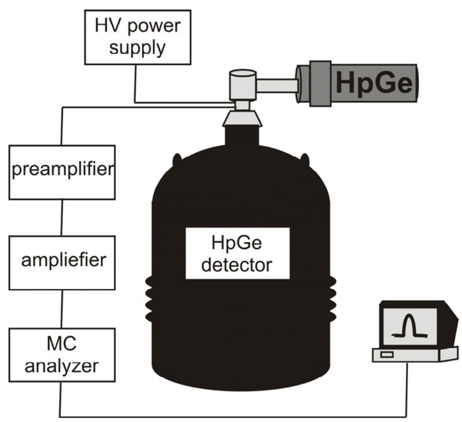


Figure 4: The scheme of Doppler broadening of annihilation gamma line 511 keV spectrometer.

It consists of HV adapter, HpGe detector, a preamplifier, a multichannel analyser and a computer Annihilation quanta are registered by a detector made by BALTIC SCIENTIFIC INSTRUMENTS. Its parameters are given in the table.

Table 2: Main Parameters of HpGe Detector

| Feature | Value |
|---|---|
| relative registration efficiency at 1.33 MeV-photon | 30% |
| energy resolution FWHM for energy 511 keV | <1250 eV |
| peak to Compton ratio | 58:1 |
| energy range of detector operation intensity | 40 ÷ 10 000 keV |

## SUMMARY

Completion date of PAS measurements unit by LEPTA project is expected to be the end of 2012. First results are predicted to be obtained at the beginning of 2013. The research is going to concern mostly materials engineering, both in metals and semi-conductors. The main research is going to include studies on the influence of surface treatment processes on the defecting of the surface layer in materials which are commonly used in industry, such as stainless steel. Furthermore, plans are made to conduct research oriented around thin layers and layers created by ion implantation. In further perspective there are plans to develop the equipment for registering two gamma quanta in a coincidence, which would significantly reduce the background in the spectrum.

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