The study of nanolayer materials and artificial diamonds by positron spectroscopy using a slow monochromatic positron injector, unique in Russia

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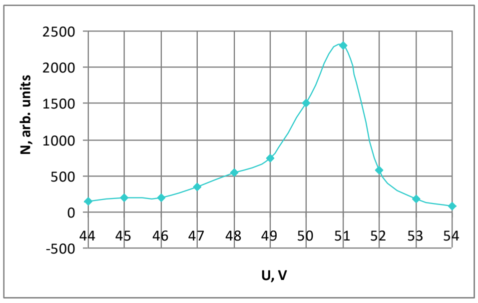
The series of works consists of 8 papers.

To study the structure of materials and defects that occur under various physical influences (aging, external loads, radiation), high-precision methods are required that can distinguish the inhomogeneities of the crystal structure at the nanometer level. One of these methods is positron annihilation spectroscopy (PAS). This method is sensitive to the detection of so-called "open–volume" defects - size from 0.1 to 1 nm with a minimum concentration of up to 10^{-7} cm^{-3}, it has 4 times better spatial resolution, for example, compared with a transmission electron microscope.

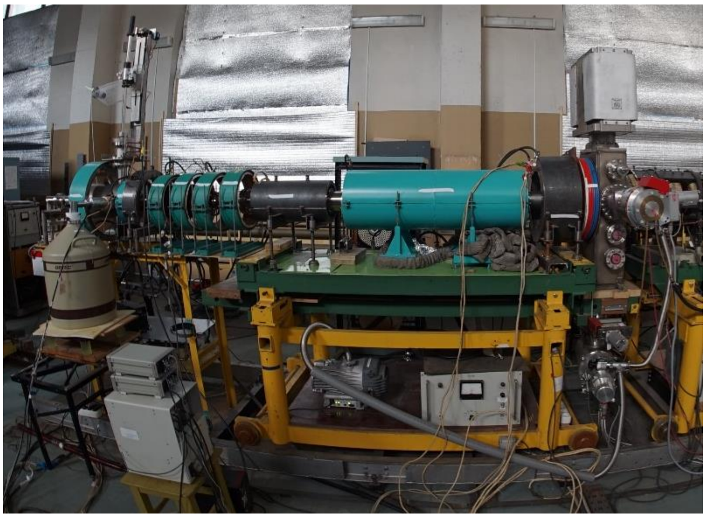
An installation that allows generating a monochromatic flow of slow positrons is required to carry out measurements using Positron Annihilation Lifetime Spectroscopy (PALS) and Doppler Broadening of the Annihilation Line (DBAL). It has a fundamental advantage over widespread isotope sources with a wide energy spectrum of positrons. By changing the energy of the positrons, it is possible to scan samples for defects in depth with extremely high accuracy, avoiding the accepted method of mechanical removal of layers of the material under study.

The installation created at the Laboratory of Nuclear Problems named after V. P. Dzhelepov JINR has a Cryogenic Source of Slow Monochromatic Positrons (CSSMP). Positrons emitted during the decay of the isotope ^{22}Na are characterized by a wide energy spectrum. They lose their energy at ionization losses up to thermal velocities in a solid-state moderator. Solid neon was chosen as a moderator. It sprayed onto a metal (stainless steel) surface and directly onto a "tablet" of the isotope ^{22}Na, cooled to a temperature of 7 K.



Typical spectrum of slow positrons of a CSSMP source. Full width at half height 2 eV, positron output 3.3×10^{6} positrons per second

The CSSMP allows you to create a low-energy positron beam that satisfies the requirements of the PAS methods in terms of its parameters. An additional possibility of adjusting the energy of positrons appears when the sample is "suspended" under a negative potential that accelerates positrons, which allows monoenergetic positrons of a given energy penetrating to a certain depth into the sample.



Installation of the Positron Injector DLNP JINR

The first implemented method on an injector using a monochromatic flow of slow positrons is the spectroscopy method for measuring the Doppler broadening of the annihilation line of the annihilation gamma quantum. This method is used to detect vacancies, vacancy clusters, and determine their concentration.

Defectoscopy studies of various materials from scientific institutes and laboratories in Russia and JINR member countries are carried out at the Positron Injector facility of the DLNP JINR. This work cycle presents the results of research on radiation-resistant materials with improved physical and mechanical properties (Tomsk Polytechnic University) and the structure of synthetic diamond (Northern (Arctic) Federal University named after M. V. Lomonosov). TPU's research focuses on nanoscale multilayer coatings of Zr/Nb, which are used as structural materials in the core of nuclear reactors. Such coatings significantly increase the service life of reactors. SAFU's research is dedicated to analyzing defects that occur during electron irradiation of synthetic diamond plates doped with nitrogen. These materials are used in the development of quantum optical networks. The possibilities of using these materials to create solid-state spin qubits are also being considered.

The unique capabilities of non-destructive testing, extreme sensitivity to defect detection, and the ability to scan samples for defects in depth with extremely high accuracy make positron annihilation spectroscopy one of the most relevant and rapidly gaining popularity in Russia and the world as a method of studying materials today.

The work cycle presents the development of the Positron Injector installation and the most promising research in modern materials science in Russia.

List of papers:

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2. P. Horodek, J. Dryzek, A.G. Kobets, M. Kulik, V.I. Lokhmatov, I.N. Meshkov, O.S. Orlov, V. Pavlov, A.Yu. Rudakov, A.A. Sidorin, K. Siemek, S. L. Yakovenko, Slow Positron Beam Studies of the Stainless-Steel Surface Exposed to Sandblasting. Acta Physica Polonica Series a, March 2014, 125(3):714-717. http://przyrbwn.icm.edu.pl/APP/PDF/125/a125z3p09.pdf

3. A. A. Sidorin et al., “A Method for Measuring the Positron Lifetime in Solid Matter with a Continuous Positron Beam”, in Proc. RuPAC'18, Protvino, Russia, Oct. 2018, pp. 267-269. doi:10.18429/JACoW-RUPAC2018-TUPSA58. https://accelconf.web.cern.ch/rupac2018/papers/tupsa58.pdf

4. M. Eseev, V. I. Hilinov, P. Horodek, A. G. Kobets, V. V. Kobets, I. N. Meshkov, O. S. Orlov, A. A. Sidorin, K. Semek, Development of Positron Annihilation Spectroscopy at Joint Institute for Nuclear Research, Acta Physica Polonica Series a, August 2019, 136(2):314-317, DOI:10.12693/APhysPolA.136.314. http://przyrbwn.icm.edu.pl/APP/PDF/136/app136z2p18.pdf

5. Eseev, M.; Kuziv, I.; Kostin, A.; Meshkov, I.; Sidorin, A.; Orlov, O. Investigation of Nitrogen and Vacancy Defects in Synthetic Diamond Plates by Positron Annihilation Spectroscopy. Materials 2023, 16, 203. https://doi.org/10.3390/ma16010203

6. Laptev, R.; Stepanova, E.;Pushilina, N.; Kashkarov, E.; Krotkevich, D.; Lomygin, A.; Sidorin, A.; Orlov, O.; Uglov, V. The Microstructure of Zr/Nb Nanoscale Multilayer Coatings Irradiated with Helium Ions. Coatings 2023, 13, 193. https://doi.org/10.3390/coatings13010193

7. Laptev, R.; Krotkevich, D.; Lomygin, A.; Stepanova, E.; Pushilina, N.; Kashkarov, E.; Doroshkevich, A.; Sidorin, A.; Orlov, O.; Uglov, V. Effect of Proton Irradiation on Zr/Nb Nanoscale Multilayer Structure and Properties. Metals 2023, 13, 903. https://doi.org/10.3390/met13050903

8. K. Siemek, E.V. Ahmanova, M.K. Eseev, V.I. Hilinov, P. Horodek, A.G. Kobets, I.N. Meshkov, O.S. Orlov, A.A. Sidorin, Realization of Positron Annihilation Spectroscopy at LEPTA Facility, Proceedings of RuPAC2016, St. Petersburg, Russia, pp. 496-498, WEPSB059. https://accelconf.web.cern.ch/rupac2016/papers/wepsb059.pdf