Positron sensing of distribution of defects in depth materials

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Abstract. It was developed a non-destructive method of positron sensing, which allows to determine the distribution of defects in the depth of the material. From the analysis we can conclude that the angular distribution curves of annihilation photons (well as and on the characteristics in experiments on the lifetime, 3\(\gamma\) - angular correlation, Doppler effect) is influenced by three main factors: a) The distribution of defects in the depth of the material, their dimensions as well as parameters of the interaction of positrons with defects. With increasing the concentration of defects the intensity \(J(\alpha, \xi)\) varies more; b) Modification of the energy spectrum of slow positrons due to the influence of defects, wherein the spectrum of positrons becomes softer, and the average energy of the positron annihilation is reduced; c) Deformation of the momentum distribution of the electrons in the region of defect. The energy spectrum of electrons is also becomes softer, and the average energy of the electrons (on which positrons annihilate) is less. The experimentally were measured spectra of photons in the zone of annihilation and were calculated the distribution of defects in depth for a number of metals.

1. Introduction

As is known, a change in the physical properties of the irradiated and deformed metals, alloys, and other substances is caused not only changes in the crystal structure of the solid body, but also the electronic structure of defects [1 – 4]. When irradiation of materials by the different particles the defects is substantially irregularly distributed over the depth of the solid body and these distributions are significantly influence on the physical and chemical properties of the substance [5 – 7]. A non-destructive method of positron sensing of defect distribution in the depth of a matter is offered by us. The positrons have a unique ability to localize in areas of the crystal with excess electronic charge inherent in conventional defects in the crystal structure that allows us to solve the linkages between electronic and atomic structure. The impact of defects on the parameters of positron annihilation in metals was found by I.Y. Dekhtyar et al. [8, 9] for nickel and its alloys with iron. It is shown that plastic deformation narrows the angular correlation curves; at the maximum the count rate increases. It is caused by the appearance of excess negative charge in the region of the defect during the formation of the stress field around the dislocations. The resulting local dipoles cause polarization of S- and d-bands and positrons are effectively captured by dislocation cores, which are confirmed by numerous experimental data on angular correlation and positron lifetime. At the same time the energy spectrum of electrons in the region of defects is undergoing significant changes, the probability of annihilation of positrons with electrons on the defects is increased by reducing their annihilation in the atomic core and due to the long lifetime of positrons in these areas. To obtain quantitative results on the change in
the electronic structure of metals and alloys are currently used different models capture positrons as well as analytical ratios linking the intensity of annihilation photons with a pulsed electron spectrum.

However, these models and methods are obtained with a number of assumptions and approximations, and therefore cannot be implemented, for example, in studying the characteristics such as the distribution of defects in depth, sizes. In addition, for conducting experiments on the methods of depth-sensing and variable thickness of the absorber it is required a strict mathematical apparatus of two-photon annihilation of positrons in defective materials.

2. The main results
A detailed analysis of the previous relationships [10] for the flows of positrons in defective materials, as well as annihilation photons in experiments 2-γ angular correlation allows in a first approximation to obtain a formula for the intensity $J_\gamma(\alpha, \xi)$ depending on the concentration $n_i(h)$ defects in the form:

$$J_\gamma(\alpha, \xi) = \sum_{i=0}^{n} n_i(h) \Phi_i(\alpha, h) dh,$$

where $\alpha$ is the emission angle $\xi_i$ is the maximum depth, $n_i(h)$ is the concentration of defects in the i-type, $h$ – depth.

$$\Phi_i(\alpha, h) = \int \int \int \int \int \int \int \Phi_i(t, x, y, z, E_i, \Omega_i) \times$$

$$\times \Phi_2(E_2, \Omega_2) d\psi_{\alpha} \psi_{an}(E_1, E_2, \Omega_1) n_i(E_1 + E_4, \Omega_1 + \Omega_4) \times$$

$$\times \psi_{\gamma,\gamma'}(E_3, E_4, x, y, z) \sigma_{12}(E_3, E_4) d\Omega_1 d\Omega_2 d\Omega_3 d\Omega_4 \times$$

$$\times dE_1 dE_2 dE_3 dE_4 dy dz.$$

Here $\Phi_i$ is a modified stream of positrons; $\Phi_2(E_2, \Omega_2)$ is the concentration of electrons; $d\psi_{\alpha}$, $\psi_{an}$ is the probability of interaction and positron annihilation; $\psi_{\gamma,\gamma'}$ is the probability of departure and the passage of annihilation photons; $n_i$ is the normalized energy spectrum of the annihilation photons in the elementary act; $\psi_{\alpha}$ is the probability of escape 2 gamma rays from the sample and passing to the detectors $D_1$ and $D_2$; $\sigma_{12}$ is the detection efficiency, and $E_1 + E_4 \Omega_1 + \Omega_4$ is the energy and the solid angle of positrons, electrons and photons; $y, z$ is the coordinate. From the analysis of equations (1) and (2) we can conclude that the angular distribution curves of annihilation photons (well as and on the characteristics in experiments on the lifetime, 3γ - angular correlation, Doppler effect) is influenced by three main factors: 1. The distribution of defects in the depth of the material, their dimensions as well as parameters of the interaction of positrons with defects. With increasing the concentration of defects the intensity $J_\gamma(\alpha, \xi)$ varies more. 2. Modification of the energy spectrum of slow positrons due to the influence of defects, wherein the spectrum of positrons becomes softer, and the average energy of the positron annihilation is reduced. 3. Deformation of the momentum distribution of the electrons in the region of defect. The energy spectrum of electrons is also becomes softer, and the average energy of the electrons (on which positrons annihilate) is less.

The deformation of the energy and angular spectra of positrons and electrons, as well as an increase in the concentration of radiation-induced defects lead to the fact that the momentum distribution of the annihilating pairs varies considerably (becomes softer), the average energy of the pair in the C-system is reduced. Consequently, in the laboratory frame annihilation gamma-rays will be emitted at an angle close to 180 °, i.e. all this will lead to a narrowing of the angular correlation curves. The equation of the type (1) is a Fredholm integral equation of the second kind and it can be attributed to the number of incorrect equations which are difficult to solve directly. In this connection must be properly set up an experiment that could be used this ratio. At the same the detectors $D_1$ and $D_2$ arranged motionless on line 0 - 0 and the sample moves through the zone of annihilation in steps of $\Delta x = 0.01$ mm in the chamber using a special screw so that each measurement was conducted in the same position of the...
sample (it means that the projection on a plane perpendicular to the direction of movement of the screw) to reduce measurement errors.

The experimental intensity distribution curves $I(x)$ of the annihilation photons in the annihilation zone are shown in Figure 1. It is seen that in the irradiated samples are observed a strong increase in the intensity of annihilation photons than annealed, and the effect is at the maximum of the curve can be up to about 20 %. The effect of increasing $I(x)$ is associated with a more effective deceleration and capture of positrons in defects. All curves are asymmetric, with the right half of them falls substantially lower than the left. This is due to the fact that the moving sample sinking gradually overlaps the source of positrons and ultimately reduces the flow of the annihilation gamma rays to almost zero.

**Figure 1.** The experimental curves of the intensity distribution of photons in the zone of annihilation. a is the titanium annealed (I), 2 is the same, irradiated by $\alpha$-particles 29 MeV to integral dose $10^{15}$ cm$^{-2}$, $3 - 5 \times 10^{15}$ cm$^{-2}$, $4 - 10^{16}$ cm$^{-2}$; b is alloy (Ti + 1.2 atm.% Zr) annealed (I), 2 is the same, irradiated by $\alpha$- particles 29 MeV to integral dose $10^{15}$ cm$^{-2}$, $3 - 1.5 \times 10^{15}$ cm$^{-2}$; c is molybdenum annealed (I), 2 – irradiated by proton 30 MeV to a dose of $6 \times 10^{17}$ cm$^{-2}$

**Figure 2.** The dependence of the concentration of radiation-induced defects on the depth in titanium irradiated with alpha particles with an energy of 29 MeV (a) and molybdenum irradiated by protons with an energy of 30 MeV (b).
We have proposed a method of positron sensing vacancy defects in the depth of the material. In the case where the defect concentration (on which occurs the process of annihilation) is insignificant, the dependence \( n(x) \) on the depth can be found in the first approximation from the expression:

\[
    n(x) = \frac{d}{dx} \left( \frac{J_2 - J_1}{J_2} \right) \frac{n_0}{\Phi(\alpha, x)}.
\]

The experimental measurements of the curves intensity distribution of annihilation photons in the annealed and irradiated samples were performed on an automated installation of the angular correlation with program management.

In this way, inputted defects change the interaction of positrons with materials. Using this method one can determine the concentration of defects at a given depth. According to the experimental results dependencies \( J_1(h) \) and \( J_2(h) \) with taking into account the actual zone of positron annihilation as they pass through the sample, we obtained depth profiles of defects in titanium alloys irradiated with alpha particles with energy of 10 - 30 MeV, with application of the relations (13).

The calculation results are shown in Figure 2. It can be seen that the concentration of defects uniformly distributed over the depth of the samples of titanium and molybdenum. Thus, the method of positron depth sensing allows to determine the distribution of defects in the depth of the material. Comparing these results with those curves calculated by the method of variable thickness of the absorber and the cascade-probabilistic method [10], have them satisfactory agreement.

3. Conclusion
1. It is proposed and developed a method of positron-sensing defect distribution in the depth of the material.
2. For the first time were received the experimental intensity distributions of photons directly in the zone of annihilation for annealed and irradiated samples of Ti and Ti + 1,2 % Zr (\( \alpha \)-particles) to different doses and on Mo, irradiated by proton on the basis of which are determined the distributions of defects in depth, consistent with theoretical calculations.

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References
[1] Kupshishin A I, Potatiy K V and Chukurova R M 1987 Cryst. Latt. Defects and Amorphous Mater. 13 (34) 157–162
[2] Luccasson P G, Wolker R M 1961 Disc. of the Faraday Soc. 31 57–66
[3] Howell R H 1978 Phys. Rev. B18 (7) 3015–3025
[4] Mitchell J B, Logan G M and Echer C J 1973 J. Hucl. Mater. 48 139–142
[5] Lisitsyn V M, Korepanov V I and Yakovlev A N 2000 Proceeding of 11th conf. On Radiation Phys. And Chem. Of Condensed Matter. (Tomsk, TPU) 125–128
[6] Lisitsyn V M, Korepanov V I and Yakovlev A N 2006 News of higher educational institutions. Physics 10 98–101
[7] Korepanov V I, Lisitsyn V M and Lisitsyna L A 1997 Russian Physics Jour. 39 (11) 1082–92
[8] Dekhtyar J 1975 Electronic structure of defects in metals Metal, electronic, D lattice, Naukova Dumka 228–252
[9] Dekhtyar I Ya 1974 Physics Reports 9 C 5 243–353
[10] Boos E G, Kupchysyn A I, Kupchysyn A A, Shmygalev E V, Shmygaleva T A 2015 Contact Markov chains (Almaty KazNPU. Abaya, research institutes and NHT M Kazakh National University. Al-Farabi, LLP "Kama") 388