THE DIRECTIONAL ACTION OF METAL-METAL CONTACT ON THE DIFFUSIVE MOVEMENT OF POSITRONS*

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Angular distributions of annihilation photons have been measured for several thin layer bimetallic samples. It was obtained that each of the distributions is more similar to a distribution characteristic of one of the sample components than could be expected from the weight composition of the sample. This may be interpreted as a result of directional action of metal-metal contact on the diffusive movement of positrons. The observed directions of positron penetration through the contacts are in good agreement with theoretical calculations of the positron work functions for metals.

1. Introduction

Positrons from radioactive source penetrating into the metal lose their kinetic energy in a relatively short time, and then, already thermalized, undergo diffusive movement. According to theoretical calculations [1] and results of respective experiments [2, 3] the diffusion length for positrons in metals is of order of 10^{-7} m. Thus, when the positron is slowed down in the metal at a distance from its boundary of order of the diffusion length or nearer, it can reach the boundary before annihilation. For some metals a result of this process is the emission of slow positrons [2, 4, 5] which may be used for the formation of a monoenergetic beam of low energy positrons useful in positron-atom scattering experiments. Since thermalized positrons can escape from some metals, it is concluded, their positron work functions are negative. Calculations performed by Tong [6] and then by Hodges and Stott [7] and by Nieminen and Hodges [8] permit one to estimate positron work functions for many metals. Experimental evidence supporting the reliability of these calculations based on observations of slow positron emission from metals is rather difficult. When the positron emission takes place it is necessary to measure positron energies with great accuracy. The absence of the emission allows one only to conclude

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that the positron work function is positive. Moreover, as it follows e. g. from Canter's observations [5], the surface purity may have a great effect on the course of this phenomenon.

By studying positron annihilation in thin layer bimetallic systems, Świątkowski et al. [3] found that the metal-metal contact acts directionally on diffusive movement of positrons. The effect can be explained as a result of the different values of the positron work function for metals producing the contact. Observation of this effect for a large number of metal contacts can permit one to put the metals in order according to values of their positron work functions. This ordering of metals may be, in turn, a criterion of the reliability of positron work function calculations.

In this paper the results of the study of the angular distribution of annihilation photons (ADAP) for several bimetallic samples will be presented as well as the comparison of observed directions of positron diffusion from one metal to other with those directions expected from positron work functions estimated by Hodges and Stott [7] and Nieminen and Hodges [8].

2. Energy barrier for positrons on a metal-metal junction

The energy barrier for positrons on the boundary between two metals (say metal A and metal B) is determined by the positron inner chemical potentials μ_A and μ_B in the metals as well as by the energy barrier D_{AB} connected to the dipole layer on the contact. With these terms the whole energy barrier Φ_{AB} for positrons on the contact can be written:

$$\Phi_{AB} = -D_{AB}-\mu_A+\mu_B. \tag{1}$$

For negative value of Φ_{AB} the contact should let positrons pass from metal A to metal B only (of course with the additional limit that the barrier is greater than the kinetic energy of thermalized positrons). The chemical potential consists of two components, first the positive zero point energy E_0 due to the motion of the positron in the ionic lattice, and second the negative electron-positron correlation energy E_{corr}. Thus

$$\mu = E_0+E_{\mathrm{corr}}. \tag{2}$$

E_0 and E_{corr} as well as D_{AB} may be estimated from the electronic structure of metals forming the contact. The calculated values of E_0, E_{corr} and the surface barrier D on the metal-vacuum boundary for some simple and transition metals are given in [7] and [8] respectively (both papers include results for noble metals also). With these terms the energy barrier on the metal-metal contact may be given by the formula:

$$\Phi_{AB} = D_B+E_{0,B}+E_{\mathrm{corr},B}-D_A-E_{0,A}-E_{\mathrm{corr},A}, \tag{3}$$

where it was assumed that the dipole barrier on the metal-metal contact (D_{AB}) equals the difference of the surface barriers D_A and D_B. Then:

$$\Phi_{AB} = \Phi_A-\Phi_B, \tag{4}$$

where Φ_A and Φ_B denote the positron work functions for metal A and metal B, respectively. The positron work functions for some metals taken from [7] and [8] are presented in Table I.

TABLE I

Positron work functions for metals

Metal	$\Phi = -D-E_0-E_{corr}$ (eV)	
	Hodges and Stott [7]	Nieminen and Hodges [8]
Sn	2.7	—
Cd	1.8	—
Zn	0.9	—
Al	0.7	—
Ag	0.3	2.4
Cu	−0.9	0.8
Au	−1.6	1.1
Ni	—	−0.4
Fe	—	−0.8

3. *Positron annihilation in a bimetallic system*

Let us consider a sample consisting of little fragments of two metals, say metal A and metal B, the dimensions of the fragments being small (at least along the positron beam) compared with positron range. When the sample is irradiated by positrons from a radioactive source, then according to the absorption law, the number of positrons absorbed in each of the metals is proportional to the weight content of the metal in the sample. Thus, if the positrons annihilate in the metal in which they were slowed down during the absorption process the angular distribution of annihilation photons (ADAP) for the bimetallic sample, f_{AB}, should be a superposition of ADAP f_A and f_B for metal A and metal B given by the formula

$$f_{AB} = af_A+(1-a)f_B, \tag{5}$$

where a and $(1 - a)$ are the weight contents of metal A and metal B in the sample, respectively. When the metal-metal boundary between monometallic fragments allows positrons to pass it in one direction only, say from metal B to metal A, some of the positrons slowed down in metal B can penetrate to metal A before they annihilate. In such a case we have

$$f_{AB} = bf_A+(1-b)f_B, \tag{6}$$

where $b > a$. Thus the shape of ADAP for a bimetallic sample is determined both by the weight content of the sample and by the directional action of the metal-metal contact on the diffusive movement of positrons. The determination of parameter b from the experimental ADAP for the bimetallic sample and for respective monometallic samples and its

comparison with the parameter a determined by the sample content allows one to find the direction of positron diffusion flow through the contact, and then, according to the formula (4), the sign of the difference $\Phi_A - \Phi_B$.

4. Experiment and its results

4.1. Investigated systems

The ADAP for several bimetallic samples consisting of deposited alternately thin layers of two metals and for respective monometallic samples have been measured. The multilayer samples Ag–Cu, Ag–Zn and Cu–Zn as well as monometallic samples Ag, Cu and Zn have been prepared by means of the evaporation technique, similarly as was done earlier for the Ag–Cd system in [3]. The bimetallic sample Cd–Sn and monometallic samples Cd and Sn were prepared electrolytically. Thicknesses of the layers in investigated bimetallic samples were close to 10^{-7} m. The necessity of preparing the monometallic samples by the evaporation technique (Ag, Cu and Zn) or electrolytically (Cd and Sn) was associated with

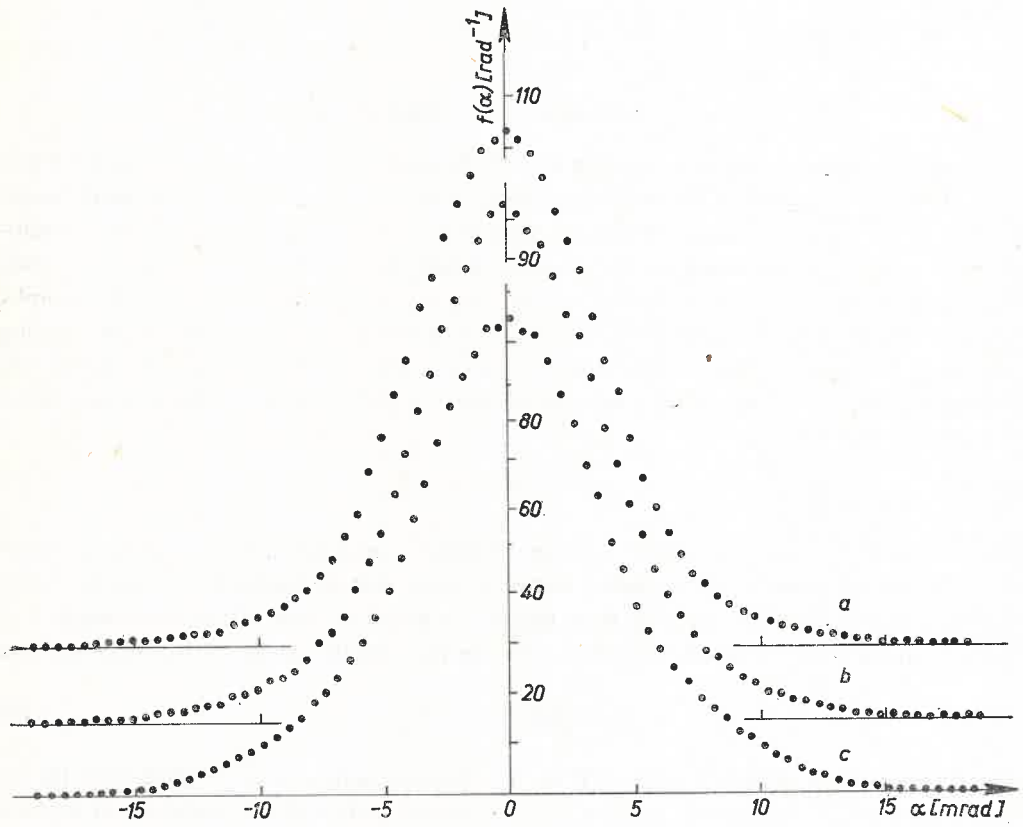

Fig. 1. Angular distributions of annihilation photons for evaporated samples Zn — a, Ag — c and Ag–Zn — b

the fact that the ADAP for bulk samples may differ from those obtained electrolytically or by evaporation. For instance it was found for the evaporated monometallic samples examined here, similarly as was observed earlier for Bi and Cd [9], that the ADAP corresponding to them differ from those corresponding to respective bulk samples. Only for Ag is the ADAP for an evaporated sample practically identical with the ADAP for a bulk sample.

4.2. The measurement of ADAP

The ADAP have been measured by means of the two-photon annihilation spectrometer described in [10]. The numbers of coincidences at maxima were greater than 10,000 for all measured ADAP. The background due to random coincidences was nearly equal to 1% of maximum.

As an illustration the ADAP obtained for evaporated samples Ag, Zn and Ag–Zn (containing of 46 weight % Ag and 54 weight % Zn) are presented in Fig. 1.

4.3. Results

To determine the direction of diffusive flow of the positrons from one metal to the other, it was necessary to find for each bimetallic sample parameter b determined by (6) and to compare it with the respective parameter a resulting from the sample composition. Parameter b was estimated by the least square method from the condition of best fitting of the determined by (6) ADAP (using the experimental ADAP for monometallic samples) to experimental ADAP for the bimetallic sample. This leads to the formula

$$b = \frac{\sum_i W_i[f_B(\alpha_i)-f_{AB}(\alpha_i)]\,[f_B(\alpha_i)-f_A(\alpha_i)]}{\sum_i W_i[f_B(\alpha_i)-f_A(\alpha_i)]^2}, \tag{7}$$

where W_i denotes the statistical weight connected with observations at a given angle α_i. Taking into account that the statistical weight is greater the greater the difference $f_A(\alpha_i)-f_B(\alpha_i)$ is, and that the standard error changes approximately as $[f(\alpha_i)]^{1/2}$, it was assumed that

$$W_i = \frac{|f_A(\alpha_i)-f_B(\alpha_i)|}{\sqrt{f_{AB}(\alpha_i)}}. \tag{8}$$

The respective differences of ADAP for the case of Ag–Zn system are shown in Fig. 2. Taking into account that although the steps between experimental points for each ADAP are equal but coordinates (α_i) are different for them, the differences were obtained by taking as $f(\alpha_i)$ for each respective ADAP, where $\alpha_i = 0.5, 1.0, 1.5, \ldots$ mrad, the mean value $1/2\,[f(\alpha_i')+f(\alpha_i'')]$, where α_i' and α_i'' are coordinates of two experimental points for which α_i' and $-\alpha_i''$ are closest to α_i. For the purpose of transparency the standard errors are plotted in Fig. 2 for the differences $f_{Ag}(\alpha_i)-f_{Ag-Zn}(\alpha_i)$ only. As the distributions f_{Ag}, f_{Zn} and f_{Ag-Zn} for angles greater than 15 mrad practically do not differ, the differences are presented for the 0–15 mrad region only.

It was found for each of the examined bimetallic samples that the ADAP corresponding to it is more similar to that ADAP corresponding to one of the metals composing the sample than could be expected from formula (5). For instance Fig. 2 indicates that the ADAP for Ag-Zn sample is more similar to the ADAP foı Zn than follows from the composition

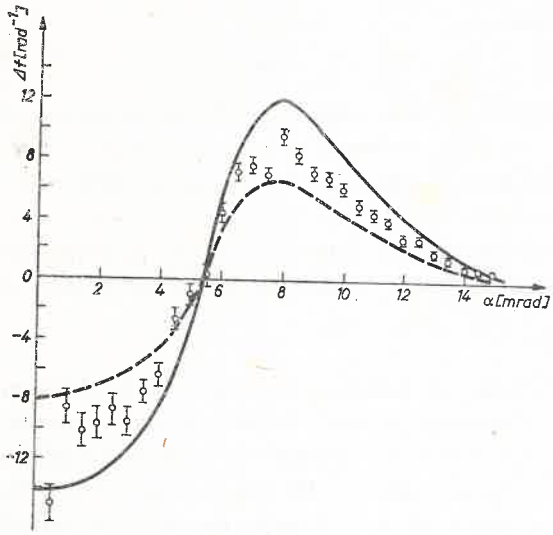

Fig. 2. Differences between angular distributions of annihilation photons: $(f_{Ag} - f_{Zn})$ — solid line; $(f_{Ag} - f_{Ag-Zn})$ — experimental points. The dashed line presents the difference $(f_{Ag} - f_{Ag-Zn})$ expected from relation (5)

of the Ag–Zn sample only. Similar results were found for other bimetallic systems also. Observed deviations from formula (5) indicate that positrons can penetrate through respective metal-metal contacts from Cu to Ag, from Cu to Zn, from Ag to Zn and from Cd to Sn.

5. *Final remarks*

The direction of positron diffusion through metal-metal junctions observed both in this work and earlier in [3] can be explained by assuming that the respective positron work functions fulfil the relations

$$\Phi_{Cu} < \Phi_{Ag} < \Phi_{Cd} < \Phi_{Sn} \tag{9a}$$

and

$$\Phi_{Ag} < \Phi_{Zn}. \tag{9b}$$

The above inequalities are in good agreement with the results of Hodges and Stott positron work function calculations [7]. The positron work functions for noble metals calculated by Nieminen and Hodges [8], although are in agreement with the experimentally obtained

inequality $\Phi_{Cu} < \Phi_{Ag}$, seem to be too great. The calculated by them value 2.4 eV for Φ_{Ag} needs positrons to penetrate from Cd to Ag, the fact being in discrepancy with experiment [3]. The observed positron emission from Au and Cu [11] indicates negative positron work functions for these metals which is also in contradiction with the results of [8] and agrees with [7].

From the above considerations it is clear that measurements of ADAP for bimetallic samples in which, as a result of the directional action of the metal-metal contact the diffusive penetration of positrons from one metal to the other takes place, may give essential information about the interaction of positrons with metals and, thus, about their electronic structure.

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