POSITRONS AT METAL BOUNDARY

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ABSTRACT. Current knowledge of positron-metal boundary interaction is reviewed. The review interlinks such phenomena as positron trapping at surface, escape of positrons from metals, directional action of metal-metal contact on diffusive movement of positrons and interaction of slow positron beam with surfaces.

1. INTRODUCTION

The positron was discovered by Anderson [1] 55 years ago. Being the antimatter equivalent of the electron, the positron has the same spin and mass as the electron but opposite electric charge and opposite spin-magnetic moment mutual orientation. The positron is a stable particle; however, in ordinary matter, where approximately one third of the elementary objects are electrons, the positron decays in a very short time annihilating with one of the matter electrons. Because the energy-loss cross sections are high, positrons usually slow down to almost thermal energies before annihilation [2], even though they are formed with million electron-volt energies in beta decay and pair production. The positron lifetime ($\sim 10^{-10}$ second [3]) and the total momentum, carried away by annihilation photons (in most cases an e^+e^- pair annihilates with emission of two photons), give useful information about the environment in which positrons have been implanted. It is therefore not surprising that the positron techniques have been responsible for a number of interesting results in the study of condensed matter [4]. Positron annihilation offers a unique probe for the detection of vacancies in metals [5, 6], for measuring the characteristics of the Fermi surface of metals and alloys [7, 8] and for the observation of the quantum chemistry phenomena associated with the particle of very light mass [9]. It must also be mentioned that the positron and the electron can bind together to form a light atom called positronium, first observed in 1951 by Deutsch [10].

Positrons thermalized in the metal perform diffusive movement which, as a rule, ends in the annihilation of positron-electron pairs. According to theoretical calculations [11] and results of respective experiments [12–14] the

diffusion length for positrons in metals is of the order of 10^{-7} m. Thus, when the positron is slowed down (implanted as a result of absorption of a positron beam) in the metal at a distance from its boundary of the order of diffusion length or nearer, it can reach the boundary before annihilation. In this case the further fate of the positron depends on the boundary action on it. Observing results of this action one can obtain information about the surface properties of the boundary.

Depending of the character of the boundary there are four possibilities for the positron reaching the boundary:

1) the positron is trapped in the boundary region;
2) the positron passes through the boundary (e.g. escape of low energy positrons from the metal);
3) the positron is "reflected" by the surface of the boundary and continues its diffusive movement;
4) the positron forms at the boundary a positronium atom which can be either trapped at the boundary or emitted from the metal.

The metal emitting low energy positrons ("anticathode") allows one to obtain monoenergetic positron beams. The advantage of a beam of positrons is that one can investigate samples that are too thin to thermalize a significant fraction of the high energy beta-decay positrons of the usual experiments. It is thus possible to study the unique interactions of positrons with surfaces under controlled conditions.

2. POSITRON POTENTIAL ENERGY AT METAL-VACUUM BOUNDARY

According to Hodges and Stott [15, 16] as well as Nieminen's and Hodges' [17] considerations the potential energy $V(x)$ at a distance x from a metal surface has the shape presented schematically in Fig. 1. Inside the metal

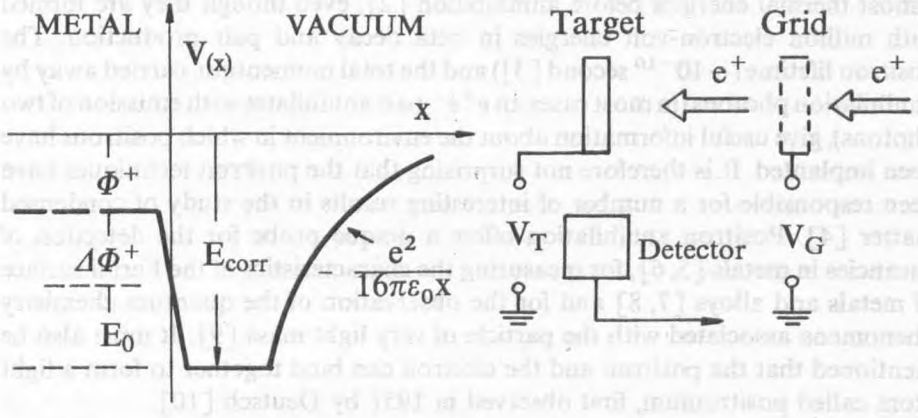

Fig. 1. A schematic plot of the positron potential energy near a metal surface.

Fig. 2. A schematic diagram of the retarding field analyzer.

$V(x)$ may be regarded as a constant equal to the positron work function Φ^+ taken with changed sign, and being a sum of three terms:

1) the band structure energy E_0 due to repulsive positron-ions interaction;
2) the positron-electron correlation energy, E_{corr};
3) the surface contribution $\Delta\Phi^+$ due to the dipole layer at the metal surface.

This means that

$$\Phi^+ = -\mu^+ - \Delta\Phi^+, \tag{1}$$

where

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

is the chemical potential.

Far from the metal $V(x)$ should be given by the classical image potential i.e.

$$V(x) = -e^2/16\pi\varepsilon_0 x. \tag{3}$$

For $\Phi^+ < 0$ thermalized positrons can escape from the metal with kinetic energy close to $-\Phi^+$ (i.e. ~ 1 eV) and may be used for the formation monoenergetic positron beams [18–20].

Measurements of slow positron yield and of Φ^+ can be made using the retarding field analyzer which is schematically shown in Fig. 2. Positrons entering the target when reemitted may, depending on the target bias and their kinetic energies, escape through the grid or be returned to the target annihilating within it. Thus the total count rate Y of the detector of annihilation radiation from the target changes with the target bias as is shown in Fig. 3. As it is seen from Fig. 3, it is possible to measure the positron work function Φ^+ simultaneously with the contact potential difference [equal to

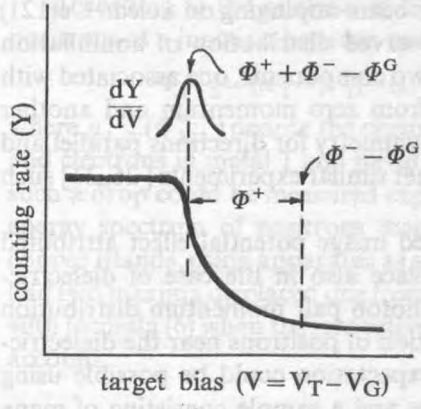

Fig. 3. The dependence of the counting rate on target bias (see Fig. 2).

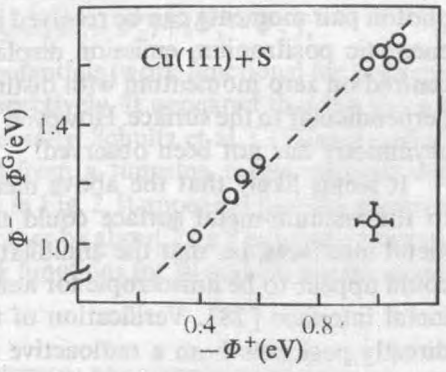

Fig. 4. Comparison of the changes in electron work function with those of the positron work function (ref. [21]).

$(1/e)(\Phi^- - \Phi^G)]$ between target and grid. Φ^- and Φ^G denote electron work functions for the target and grid materials, respectively.

It should be remembered that the electron work function for a metal is equal to

$$\Phi^- = -\Delta\Phi^- - \mu^-, \tag{4}$$

where μ^- is the electron chemical potential, and

$$\Delta\Phi^- = -\Delta\Phi^+ = \Delta\Phi. \tag{5}$$

The terms μ^+ and μ^- are determined by the metal interior whereas $\Delta\Phi$ depends on the surface conditions. Thus, according to Eq. (5), when a change of surface conditions increases the positron work function, it must decrease as much the electron work function. This has been noticed by Murray and Mills [21] who observed positron reemission from Cu(111) surfaces coated with different amounts of S (Fig. 4).

3. ANNIHILATION OF POSITRONS TRAPPED AT METAL BOUNDARY

An important feature of the potential energy shown in Fig. 1 is the appearance of a potential "trough" for positrons at the metal surface, in which the positron can be trapped. Analysis of the wave function of a positron trapped in such a "trough" as well as of the metal electron wave functions in the region occupied by the trapped positron predicts an anisotropy of the distribution of momenta of photon pairs resulting from annihilation in this "trough" [22–24]. A direct verification of this prediction was possible using slow positron beam sources. When positrons with energy of the order of 1 keV enter into the metal most of them can diffuse back to the surface and be trapped there.

Howell et al. [25] using a 740 eV positron beam impinging on a clean Cu(121) surface has found that in this case the observed distribution of annihilation photon pair momenta can be resolved into two components, one associated with energetic positronium emission displaced from zero momentum and another centred on zero momentum with distinct asymmetry for directions parallel and perpendicular to the surface. However, in other similar experiments [26, 27] such asymmetry has not been observed.

It seems likely that the above mentioned image potential effect attributed to the vacuum-metal surface could take place also in the case of dielectric-metal interfaces, i.e. that the annihilation photon pair momentum distribution could appear to be anisotropic for annihilation of positrons near the dielectric-metal interface [28]. Verification of this expectation could be possible using directly positrons from a radioactive source and a sample consisting of many alternately deposited thin metal and dielectric layers. For a metal layer thickness close to the positron diffusion length or less, a large fractions of the positrons stopped in the layers should be able to reach, as a result of diffusive

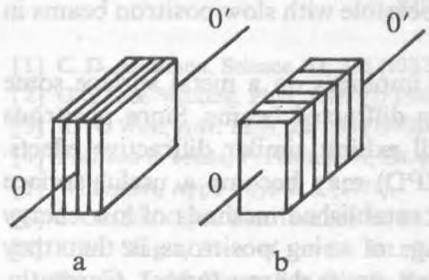

Fig. 5. Two orientations of the multilayer sample with respect to the spectrometer axis in refs. [28] and [29].

movement, the interface and be trapped there, obviously if a trapping "trough" exists. Using such multilayer samples (Al–Al_xO_y in the first experiment [28] and Ag–Na_3AlF_6 in the second [29]) and directing them in two manners with respect to pair-momentum annihilation spectrometer axis (Fig. 5), Ewertowski and Świątkowski had observed that the distribution of the annihilation pair momentum component perpendicular to the axis depends on the sample orientation. For both samples (Al–Al_xO_y and Ag–Na_3AlF_6) the distributions appeared to be narrower in the case when the momentum component parallel tc the metal-dielectric interface was analyzed (Fig. 5b). These results are in agreement with the supposition that positrons can be trapped at metal-dielectric interface.

4. POSITRONS AT METAL-METAL INTERFACE

In 1974 Świątkowski [30] suggested that the contact of two different metals could act directionally on the diffusive motion of thermal positrons allowing them to penetrate the contact in one direction only. This assumption has been confirmed experimentally. The characteristics of annihilation radiation observed for multilayer bimetallic sample appeared to be more similar to those characteristic for one metal-component of the sample as it could be expected from its content in the sample [13, 31].

According to the analysis by Stott and Kubica [32] the potential drop for positrons at a junction between two metals (say metal 1 and metal 2) is given by

$$\Phi_{1-2}=(\mu_1^+-\mu_2^+)+(\mu_1^--\mu_2^-)=(\Phi_1^+-\Phi_2^+)+(\Phi_1^+-\Phi_2^-), \tag{6}$$

where $\mu_{1,2}^{+,-}$ ($\Phi_{1,2}^{+,-}$) denote the chemical potentials (work functions) for positrons and electrons in metal 1 and metal 2, respectively. It appeared that the value of such a drop could be measured experimentally. Schultz et al. [33] analyzed the energy spectrum of positrons reemitted from a tungsten target covered with copper islands, using apparatus as shown in Fig. 2. It appeared that the spectrum had two maxima displaced one from the other by about 2.6 eV in good agreement with formula (6) when the respective work functions for W and Cu are taken into account.

5. INTERACTIONS OF SLOW POSITRON BEAM WITH SURFACE

Up to now processes connected with reaching the surface (or interface) by thermal positrons diffusing in metal were presented. The consequent use of

positrons for surface diagnostic is however possible with slow positron beams in UHV apparatus only.

When a monoenergetic positron beam impinges on a metal surface some positrons can be reflected elastically giving diffracted beams. Since positrons have the same mass as electrons, they will exhibit similar diffractive effects. Thus low energy positron diffraction (LEPD) may become a useful surface analysis technique complementing the well established methods of low energy electron diffraction (LEED). The advantage of using positrons is that they interact with the solid in a simpler way (e.g. no exchange forces). Currently, however, positron diffraction cannot be called a practical technique because of the limited intensity of slow positron sources. Nevertheless, some interesting results have been obtained. As an example in Fig. 6 we present the results of Canter's LEED and LEPD observations for Cu(111) surface [34].

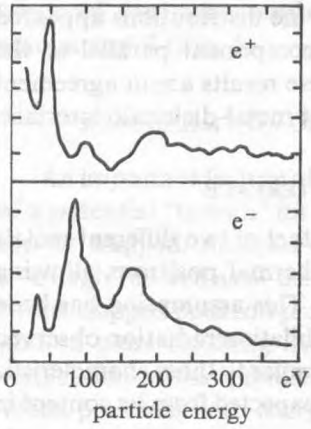

Fig. 6. Comparison of positron and electron diffraction on Cu(111) surface for equal incidence and reflection angles (30°) [34].

A great part of the positrons impinging on the surface takes part in many nonelastic processes leading to their thermalization. For example, a fast positron can stimulate the emission of a secondary electron which can be used as time marker in positron life-time measurements [35]. The results obtained by Weiss and Canter [36] showed that the efficiency of the emission of secondary electrons and their energy spectra are similar if the emission is stimulated either by electrons or by positrons.

Reemission of nonthermalized positrons is also possible. When the reemission is preceded by excitation of a small number of plasmons one can observe, similarly as in electron scattering, the appearance of characteristic energy losses [37].

6. FINAL REMARKS

The aim of this paper was to present to the reader a not widely known branch of physics, namely slow energy positron physics, and especially its possibilities in studies of the metal boundary. Due to the very rapid development of slow positron beam techniques one may hope that in the nearest future positron techniques become almost as useful for surface studies as other traditional and well-established techniques are now.

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REFERENCES

[1] C. D. Anderson, Science, **73**, 238 (1932).
[2] G. E. Lee-Whiting, Phys. Rev. **97**, 1557 (1955).
[3] R. N. West, Adv. Phys. **22**, 263 (1973).
[4] Positron in solids, P. Hautojärvi, Ed. (Springer Verlag, Berlin–Heidelberg–New York 1979).
[5] W. Brandt, Appl. Phys. **5**, 1 (1974).
[6] S. Chabik, Cryst. Res. Technol. **12**, 1523 (1987).
[7] R. M. Singru, Proc. of the 6th Int. Conf. on Positron Annihilation, P. G. Coleman, S. C. Sharma, L. M. Diana, Eds. (North–Holland, Amsterdam–New York–Oxford 1982) p. 271.
[8] M. Szuszkiewicz, Acta Univ. Wratisl. Mat. Fiz. Astr. **25**, 1 (1977).
[9] Reviewed by H. Ache, in Proc. of the 5th Int. Conf. on Positron Annihilation, R. R. Hasiguti, K. Fujiwara, Eds. (Jap. Inst. of Metals, Aoba Aramaki, Sendai 980, 1979), p. 31.
[10] M. Deutsch, Phys. Rev. **82**, 455 (1951).
[11] B. Bergersen, E. Pajanne, P. Kubica, M. J. Stott, C. H. Hodges, Solid State Commun. **15**, 1377 (1974).
[12] S. Pendyala, J. Wm. McGowan, Can. J. Phys. **52**, 1051 (1974).
[13] W. Świątkowski, B. Rozenfeld, H. B. Kołodziej, S. Suszkiewicz, Acta Phys. Polon. **A47**, 79 (1975).
[14] M. Dębowska, A. Baranowski, phys. stat. sol. (b) **117**, K127 (1983).
[15] C. H. Hodges, M. J. Sttot, Phys. Rev. **B7**, 73 (1973).
[16] C. H. Hodges, M. J. Stoot, Solid State Commun. **12**, 1153 (1974).
[17] R. M. Nieminen, C. H. Hodges, Solid State Commun. **18**, 1115 (1976).
[18] P. G. Coleman, T. C. Griffith, G. R. Heyland, Appl. Phys. **4**, 89 (1974).
[19] K. F. Canter, A. P. Mills Jr., S. Berko, Phys. Rev. Lett. **34**, 1541 (1975).
[20] D. Shödlbauer, P. Spee, G. Kögel, W. Triftshäuser, Proc. of the 7th Int. Conf. on Positron Annihilation, P. C. Jain, R. M. Singru, K. P. Gopinathan, Eds. (World Scientific Publishing Co., Singapore 1985), p. 957.
[21] C. A. Murray, A. P. Mills Jr., I. O. Rowe, Surf. Sci. **100**, 647 (1980).
[22] W. Triftshäuser, J. D. McGervey, R. M. Hendricks, Phys. Rev. **B9**, 3321 (1976).
[23] B. Rozenfeld, K. Jerie, W. Świątkowski, Acta Phys. Polon. **A64**, 93 (1983).
[24] J. Garner, R. Benedek, J. Phys. **F16**, L165 (1986).
[25] R. H. Howell, P. Meyer, I. J. Rosenberg, M. J. Fluss, Phys Rev. Lett. **15**, 1698 (1985).
[26] K. G. Lynn, A. P. Mills, Jr., R. N. West, S. Berko, K. F. Canter, L. O. Roellig, Phys. Rev. Lett. **15**, 1702 (1985).
[27] D. W. Chen, S. Berko, K. G. Lynn, A. P. Mills Jr., L. O. Roellig, R. N. West, Bull. Am. Phys. Soc. **21**, 584 (1985).
[28] R. Ewertowski, W. Świątkowski, Phys. Scripta, **35**, 745 (1987).
[29] R. Ewertowski, W. Świątkowski, phys. stat. sol. (a) **102**, 555 (1987).
[30] W. Świątkowski, Nukleonika, **19**, 79 (1974).
[31] W. Świątkowski, Acta Phys. Polon. **A54**, 457 (1978).
[32] M. J. Stott, P. Kubica, Phys. Rev. **B11**, 1 (1975).
[33] P. J. Schultz, K. G. Lynn, W. E. Frieze, A. Vehanen, Phys. Rev. **B27**, 6626 (1983).
[34] K. F. Canter, Proc. of the 6th Int. Conf. on Positron Annihilation, P. G. Coleman, S. C. Sharma, L. M. Diana, Eds. (North Holland, Amsterdam–New York–Oxford 1982) p. 138.
[35] K. C. Lynn, W. E. Frieze, P. J. Schultz, Phys. Rev. Lett. **52**, 1137)1984).

[36] H. Weiss, K. F. Canter, Proc. of the 6th Int. Conf. on Positron Annihilation, P. G. Coleman, S. C. Sharma, L. M. Diana, Eds. (North–Holland, Amsterdam–New York–Oxford 1982) p. 162.

[37] L. D. Hullet, J. M. Dale, S. Pendyala, Proc. of the 6th Int. Conf. on Positron Annihilation, P. G. Coleman, S. C. Sharma, L. M. Diana, Eds. (North–Holland, Amsterdam–New York–Oxford) p. 857.