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Abstract

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STUDY OF THE ANGULAR CORRELATION OF GAMMA QUANTA ARISING IN THE ANNIHILATION OF POSITRONS AND ELECTRONS IN BISMUTH

(Presented by Academician G. V. Kurdyumov, January 9, 1960)

The use of soft x-ray spectra for investigating the state of valence electrons in a metal, making it possible to determine their energy characteristics, does not make it possible to study the shape of isoenergetic surfaces and zones in momentum space. To determine the shape of the Fermi surface, a number of methods based on the study of magnetic, galvanomagnetic, and resonance phenomena have now been developed.

In recent years, in a number of works ([1]-[3]), the method of angular correlation in the annihilation of electron-positron pairs in metals has been used to determine the magnitude of the Fermi energy.

Because positrons, on entering metals, become thermalized, while the electrons in the lattice possess kinetic energies of the order of several electron volts, the motion of the center of mass of the pair, obeying the principle of conservation of momentum, is manifested in the deviation of the γ-rays from 180°, caused by the presence of a momentum component $p_\perp$ perpendicular to the direction of emission. Consequently, the momentum of the electrons in the lattice can in principle be obtained from measurements of the angle α, characterizing the deviation from 180°, according to the relation $\sin\alpha = p_\perp/mc$, where m is the photon mass and c is the speed of light. Usually the experiment is arranged so that what is measured is not the angle α between the γ-rays, but its projection onto the plane passing through the axis connecting the two detectors operating in coincidence and the direction of motion of the source with the specimen. Thus, the measured angle $\alpha_z = p_z/mc$.

It is not difficult to show that, from the dependence of the counting rate on the square of the angle characterizing the deviation of the direction of the γ-photons from 180°, one can determine the value of the maximum momentum* of the electrons, $p_m = \alpha_{\max}(mc)$.

The coincidence counting rate, proportional to the number of electrons with momentum p_z, is equal to

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

$$I(\alpha) = \beta N_z(p_z) = \beta(p_m^2 - p_z^2) = \beta p_m^2 - \beta \alpha_z^2 (mc)^2.$$

Thus, if the distribution of electrons over states $N_z(p_z)$ has the form of an inverted parabola, then the dependence of $I(\alpha)$ on α_z^2 should be represented by a straight line cutting off on the abscissa axis a segment equal to $\alpha_{\max}$. Precisely when $I(\alpha) = 0$, $\alpha = \alpha_{\max}$, and $p_m = \alpha_{\max}(mc)$. From the same graph one can estimate the value of the coefficient $\beta = I_{\max}/p_m^2$.

In work (4) it was first suggested that the use of metallic single crystals as the object of investigation— will make it possible to determine not only the magnitude of the Fermi energy, but also to investigate the shape of the Fermi surface of the electrons in the metal. The method proposed by the authors (^4) in 1957 had not yet been developed experimentally, although an attempt to detect the anisotropy of the Fermi surface was undertaken in work (^5).

In the present work, to study the angular distribution of the γ-quanta obtained in the annihilation of positrons and electrons, with the aim of determining the shape of the surface of maximum momenta, an apparatus was assembled that made it possible to measure the intensity of coincident pulses from photons at different angles.

The source of positrons was Na^22; scintillation counters served as detectors, and the object of study was a bismuth single crystal in the form of a plate 2 mm thick, whose base was the basal plane.

Fig. 1

Fig. 2

The specimen was placed with its base toward the emitter and was set on a goniometric table so that the z axis was directed vertically, and the direction 0—180° on the table corresponded to the x direction in the crystal. A typical angular-distribution curve is shown in Fig. 1; it corresponds to an angle ψ

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* In the case of the study of a single crystal, the average value of this momentum is determined, corresponding to a definite section of the surface in momentum space.

Fig. 3

Figure 3: Fig. 3

Fig. 4

Figure 4: Fig. 4

between the x direction in the crystal and the straight line joining the detectors, equal to 180°. Such curves, with allowance for the background, were obtained every 15° from 0 to 180°.

Fig. 3

Polar diagrams of the mean maximum momenta of electrons in the plane perpendicular to the principal axis (the basal plane), representing the section of the surface of maximum momenta for Bi in this plane, were constructed both from the half-width ($b/2$) of the distribution curves (Fig. 3a), which is unambiguously related to the maximum momentum of the electrons, and by direct determination of the mean maximum electron momenta p_m (Fig. 3b), for which the curves $I(\alpha)$ for all the crystallographic directions studied were replotted in the coordinates I—α^2 in the regions where the parabolic law is fulfilled, as shown in Fig. 2 (ˆ3). Dia-

The diagrams obtained by these methods are similar to one another, and the maximum anisotropy in the x direction (0—180°) with respect to the y direction (90°) is $\sim$ 16%. This clearly indicates the existence in a Bi crystal of an asymmetry in the form of the angular-correlation curves of γ-quanta obtained in the annihilation of positrons with electrons for different directions in Bi.

Investigation of the band structure of Bi (^{6}) revealed that the boundary of the occupied energy levels is very close to the boundary of the principal zone. The zone contains 5 electrons per atom, so that it is almost filled. It is assumed that this zone overlaps with the neighboring one. It may therefore be expected that the shape of the cross section of the surface of occupied energy levels, found from the study of the shape of the angular-correlation curves (Fig. 3), should reflect the shape of some cross section along the boundaries of the principal zone of Bi. Since in our case the shape of the cross section of the surface of occupied levels corresponds to a section in the basal plane of Bi, it should be similar to the section along the boundaries of the principal zone of Bi perpendicular to the principal axis of the crystal. Fig. 4 shows such a section (^{6}). The shaded regions contain 0.0002 el/at and correspond to the penetration of the occupied region into the external zone. Comparison of the polar diagrams (Fig. 3) with the shape of the section along the boundaries of the principal zone of Bi (Fig. 4), perpendicular to the principal axis, reveals their far-reaching similarity, which apparently is explained by the fact that the boundary of the occupied levels is very close to the boundary of the principal zone.

Fig. 4

Analysis of the results obtained leads to the conclusion that the polar diagrams both for quantities characterizing the shape of the electron-state distribution curves and for quantities characterizing their mean maximum momenta reflect the shape of the surface of occupied energy levels.

On the other hand, as is seen from the polar diagrams presented, the shape of the indicated surface exhibits anisotropy in two directions perpendicular to the principal axis of the crystal (the x and y axes), which reflects the anisotropy of the Fermi surface and with which, possibly, the anisotropy of certain properties of Bi is also associated.

It should be noted that the polar diagrams shown in Fig. 3 were constructed on the basis of the distribution curves of γ-quanta obtained in the annihilation of pairs without taking into account the finite thickness of the γ-quantum source (in our case the Bi crystal) and of the detectors. To obtain quantitative data on the magnitude of the maximum anisotropy of the shape of the indicated surface (along the x and y axes) in two directions perpendicular to the principal axis, and also to estimate the magnitude of the mean maximum momenta of the electrons in these directions, it is necessary to take into account the resolution function determined by the finite thickness of the detectors and of the source (^{3}).

Taking this into account, angular-correlation curves were obtained for three orientations of the Bi crystal: 0, 90, and 180°, from which the half-widths of the distribution curves and the magnitudes of the mean maximum momentum of the electrons were determined.

The 0—180° direction for the orientation of the crystal in our case corresponds to the x direction, and the 90° direction corresponds to the y direction in Fig. 4. From this figure one can estimate the maximum anisotropy of the shape of the cross section of the principal zone under consideration. It is 14%. From the distribution curves obtained with allowance for the vertical resolution function, the following values were obtained for the half-widths of the distribution curves –

divisions: $b_x/2 = 5.25 \cdot 10^{-3}$ rad and $b_y/2 = 5.8 \cdot 10^{-3}$ rad, and for the mean maximum momenta $p_{mx} = 3.76\,mc$ and $p_{my} = 4.22\,mc$.

Consequently, the maximum anisotropy of the shape of the surface of filled energy levels (by half-widths) is 10.5%, and the maximum anisotropy in the values of the mean maximum momenta is 12.2%. Thus, the values we have found for the maximum anisotropy are close to the values that can be estimated from the shape of the cross section along the boundaries of the principal zone perpendicular to the principal axis of the bismuth crystal.

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Note: Figure translations are in progress. See original paper for figures.