Mechanism of anomalous penetration of positrons through a crystal

I. Ya. Dekhtyar, V. T. Adonkin, É. G. Madatova, V. I. Silant'ev, and G. Dlubek

Institute of Metal Physics, Ukrainian Academy of Sciences
(Submitted June 17, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 4, 305–309 (20 August 1977)

The angular-correlation curves of annihilation photons in an Si crystal are investigated at 11, 80, and 300 K. At low temperatures, besides the narrow component corresponding to Ps atoms, satellites are observed and attest to the delocalization of the Ps atoms. The penetration of the positron through the crystal is attributed to realization of a quantum mechanism of Ps diffusion.

PACS numbers: 78.70.Bj, 71.60.+z

A phenomenon observed in the interaction of positron with single-crystal silicon was reported in[1].[1)] It turns out that relatively thick Si crystals (0.3–0.6 mm) are transparent to some degree for positrons of ^{22}Na with maximum energy ~0.54 MeV. In a number of cases the transmission coefficient of the ^{22}Na positrons reached an anomalous value equal to ~0.5 instead of the ~0.01–0.02 which is allowed on the basis of the absorption law. An investigation of the interaction of the particles passing through the Si with the surfaces of other solids has shown that these particles are Ps atoms.

Great interest attaches, however, to ascertaining the state of the positron inside the Si crystal, since it can help clarify the mechanism whereby the positrons are converted and penetrate through the crystal.

We investigated for this purpose the crystals Si(I), Si(II), and Si(III).[2)]

The spectra of the angular distribution of the annihilation photons (ADAP) were obtained for n-Si(I) single crystals at different temperatures with the aid of a long-slit spectrometer of the UA-64 type, equipped with a helium cryostat for low-temperature measurements.

Figure 1 shows the ADAP for three temperatures: 300 K (curve 1), 80 K (2), and 11 K (3). A crystal 0.3 mm thick was placed in the spectrometer with the (111) face in such a way that the measured Z component of the momentum distribution corresponded to the ⟨111⟩ direction. The angular resolution was 0.5 mrad, and the ADAP curves were obtained in steps of 0.5 mrad. The statistical error was ~1%. At low temperatures the ADAP curves show clearly a narrow component and periodically repeated sideband satellites whose intensity decreases with increasing angle θ. At the same time, at 300 K the ADAP curve does not reveal these singularities. It is these facts, heretofore not observed for silicon, which attest to the fact that the positrons in silicon have states that depend on the temperature.

The narrow component observed at low temperatures is proof that the positron is annihilated from the para-positronium state. The satellite peaks of equal half-width occupy positions corresponding to the projections of the reciprocal-

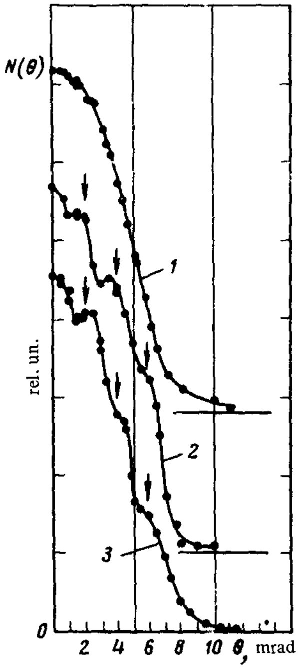

FIG. 1.

lattice vectors on the direction of the measured angular momentum of the system. The intensity of the satellite peaks relative to the central narrow component is more strongly pronounced in this case than those observed for quartz[2,3] and ice.[4]

On the basis of the simple model developed in[5], we regard the electron in a Ps atom and the other valence electrons with which the positron interacts in the silicon crystal as indistinguishable. The totality of the indicated facts then allows us to assume that at low temperatures the p-Ps in the silicon crystal is delocalized in the motion of its mass center, and its state can be described by a Bloch function. In this case the components of the large angular momenta in the annihilation spectrum are the result of the orthogonalization of the wave functions of the Ps and of the valence electrons of the crystal. The probability amplitude for the annihilating electron-positron pair has then the translational symmetry of the lattice. This corresponds to the observed picture.

The indicated state of the Ps in the Si crystal at low temperatures reveals certain feature of its behavior. First, the results indicate that the Ps is produced in the perfect regions of the lattice. Second, since the probability of the Ps delocalization in the crystal is quite large, its motion in the crystal can be regarded as a gas of quasiparticles (impuritons) having a constant velocity. This is in accord with the conditions necessary to realize the quantum-mechanical effect of impuriton tunneling.[6] Other objective factors are that

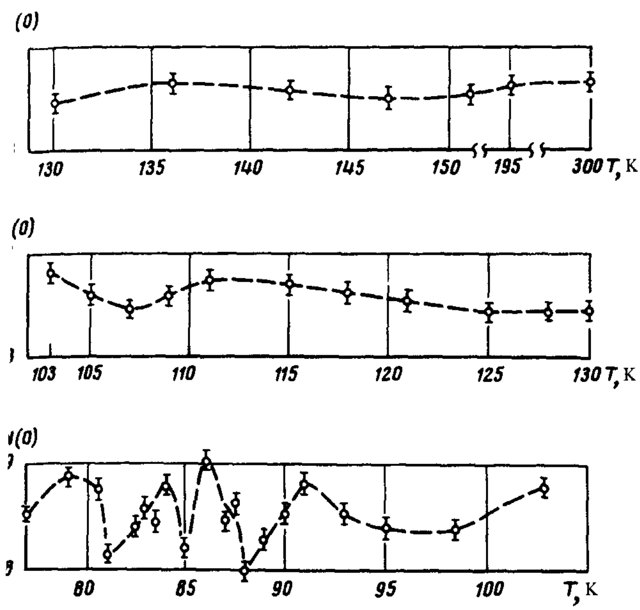

FIG. 2.

the mass of the Ps is very small, the Debye temperature $\Theta_D \sim 670$ K of Si is high enough, and the impuriton concentration is negligibly small.

All the foregoing allow us to assume that at 300 K the positronium states are substantially localized, say by capture of the Ps by lattice defects as well as by the atomic vibrations. Naturally, the penetration of the Ps in the lattice can be realized in this case by an above-the-barrier mechanism.

From this point of view, interest attaches to the temperature dependence of $N(0)$, obtained for the crystals n-Si(II) (Fig. 2) and n-Si(III) (Fig. 3).

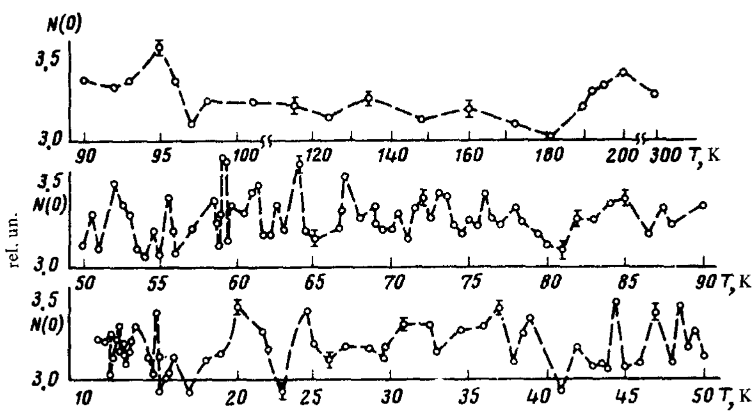

FIG. 3.

In the temperature interval 77—97 K (for Si II) and 10—97 K (for Si III) there are observed oscillations with a maximum amplitude 12 and 18%, respectively, and attenuate rapidly with further increase of the temperature. Since $N(0)$ includes a peak for Ps on the low-temperature ADAP curves (Fig. 1), the observed maxima and minima on the $N(0)$ vs T curves are evidence of a successive transition of the Ps from a delocalized to a localized state upon interaction with the lattice defects. The relatively small period of the observed oscillation is evidence of the ease with which the Ps goes over from the localized to the delocalized state. This apparently enables the Ps to leave a crystal of suitable thickness even at 300 K, as indeed was observed in[1].

We note in conclusion that according to our data the effectiveness of positron conversion and of the emergence of the Ps from the silicon crystal depends on the degree of the crystal perfection.

Further theoretical and experimental research is necessary to add to our knowledge of the Ps dynamics in crystal.

1) The first communication on this topic was made on 19 February 1976 at the Science Council of our Institute.

2) The crystals were prepared by different methods.

1. I. Ya. Dekhtyar, E. G. Madatova, V. I. Silant'ev, and V. T. Adonkin, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 691 (1976) [JETP Lett. **23**, 636 (1976)].
2. W. Brandt, G. Coussot, and R. Paulin, Phys. Rev. Lett. **23**, 522 (1969).
3. A. Greenberger, A. P. Mills Thompson, and S. Berko, Phys. Lett. **32A**, 72 (1970).
4. O. Mogensen, G. Kvajič, M. Eldrup, and M. Miloševič-Kvajič, Phys. Rev. **134**, 71 (1971).
5. C. H. Hodges, B. T. A. McKee, W. Triftshäuser, and A. T. Stewart, Can. J. Phys. **50**, 103 (1972).
6. A. F. Andreev, Usp. Fiz. Nauk **118**, 251 (1976) [Sov. Phys. Usp. **19**, 137 (1976)].