Positronium-like states in metals

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We report the first observation of positronium-like states in metallic Mo crystals at liquid-helium and liquid-nitrogen temperatures. The results indicate that delocalized positronium (Ps) is produced in definite conditions also in metals, where it can move via quantum tunneling.

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It is known that positronium production in metals is theoretically forbidden, and has not yet been observed in experiment.

In fact, it follows from a theory developed in[1] that the probability of formation in a metal of a quasi-bound state analogous to positronium is determined by a criterion that yields a parameter $\tau_0 = 2/\pi a_H R_F > 2.85$, where a_H is the Bohr radius and R_F is the Fermi wave vector. Since the real electron densities of metals, which are determined by the parameter $r_s = r_0/a_H$ (r_0 is the radius of the unit electron sphere) are such that $2 \le r_s \le 5.5$, this criterion does not hold even for metals with low electron density (large values of r_s). Taking the relation $R_F = 1.917/a_H r_s$ into account, we obtain for real electron densities of metals the condition $0.667 < \tau_0 < 1.825$. Thus, the criterion $\tau_0 > 2.85$ constitutes a hindrance of sorts to the formation and existence of positronium within the volume of the metal.

In another paper, [2] an energy criterion is proposed for Ps production in metals, and leads to refutation of such a possibility.

Nonetheless, the results obtained in[3] have demonstrated the presence of anomalous passage of positrons through relatively thick silicon crystals, as manifest by the fact that these crystals are to a certain degree transparent to positrons of ^{22}Na with maximum energy ~ 0.54 MeV. The results also indicate that the particles that have passed through the silicon crystals (thickness 0.3—0.6 mm) are Ps atoms.

Recent investigations have shown unequivocally that under certain conditions one can observe annihilation of positrons from positronium-like states that are produced inside the volume of a silicon crystal. 1) At low temperatures, the plots of the angular distribution of the annihilation protons (ADAP) reveal a narrow component that demonstrates the annihilation of positrons from a p-Ps state. In addition to the p-Ps, the ADAP curves reveal also periodically repeated sideband satellites. The temperature dependence of the counting rate $N(\theta = 0)$ at the peak of the ADAP curve is characterized by the presence of successively disposed maxima and minima, connected with the transition of the Ps from the delocalized (maximum on the $N(0)$ vs T curve) to a localized state. We report here results obtained in an investigation of the interaction

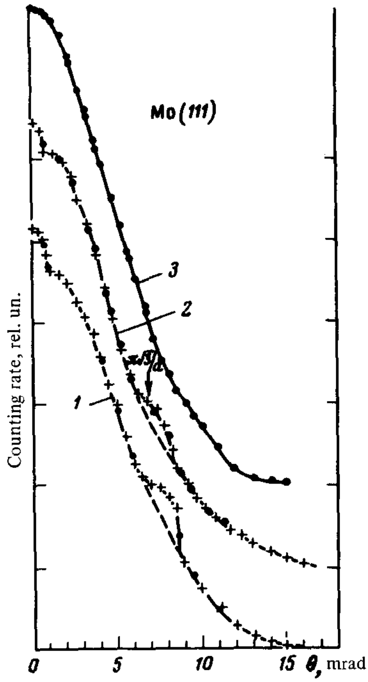

FIG. 1. Normalized ADAP curves for single-crystal Mo at 300 K (1), 81 K (2), and 7.6 K (3). The arrow marks the position of the satellite corresponding to the projection of the reciprocal-lattice vector on the direction of the measured moment.

of positrons with electrons in Mo single crystals at room and lower temperatures.

Figure 1 shows ADAP curves for the (111) face of single-crystal Mo at 300, 81, and 7.6 K. The crystal was placed in a UA-64 spectrometer with a helium cryostat in such a way that the Z component of the momentum distribution corresponded to the normal to the indicated face of the crystal. The angle of resolution was 0.8 mrad, and the statistical error ~1%.

At low temperatures, the ADAP curves show a clearly pronounced narrow component and sideband satellites, whereas these singularities are not observed at 300 K. This indicates, just as in the cited study of silicon, that the positrons in Mo crystals have temperature-dependent states. The narrow component at low temperatures is evidence of positron annihilation from the parapositronium state. The satellite peaks are observed in positions corresponding to the projections of the reciprocal-lattice vector on the direction of the measured moment of the system.

This is the first time that such a picture has been observed for metals. The presented facts indicate that at low temperatures it is possible to observe also in metals p-Ps in a delocalized state of motion of its mass center, which can be described by a Bloch wave function. It is therefore possible to apply in this case the model of[4], wherein the electron in Ps is indistinguishable from the remaining electrons in the crystal. According to this model, the sideband satellites (components of the larger momenta) in the annihilation spectrum are the results of orthogonalization of the wave functions of the Ps and of the valence electrons of the crystals. This was observed by us in metallic Mo crystals. The absence of these singularities at 300 K indicate that the delocalization of the Ps takes place in perfect regions of the lattice only at the corresponding low temperatures. Under other conditions, the Ps can be localized, for example, on lattice defects. On the other hand, under conditions of Ps delocalization in a metal, it can be regarded as belonging to the crystal as a whole, and its motion similar to the motion of a quasiparticle gas, thus corresponding to quantum-mechanical tunneling of impuritons.[5] Experiments aimed at determining the character of the motion of Ps in metals are now under way.

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