Scientific Session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (February 26, 1992)

Usp. Fiz. Nauk **162**, 177–179 (August 1992)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on February 26, 1992 in the P. L. Kapitsa Institute for Physics Problems. The following reports were presented at the session:

1. *V. P. Mineev.* $U_{1-x}Th_xBe_{13}$—a heavy-fermion superconductor.

2. *Yu. N. Ovchinnikov.* Critical current and quantum creep in layered superconductors.

A brief summary of one report is given below.

V. P. Mineev. *$U_{1-x}Th_xBe_{13}$—heavy-fermion superconductor.*

Uranium and cerium compounds, discovered about 10 years ago, form a special class of metals, in which the effective mass of the electrons is tens and hundreds of times greater than the electron mass in vacuum. The physics of compounds with heavy fermions is an odd mixture of phenomena, previously studied in pure form in the theory of the Kondo effect, the physics of superconductivity, and the physics of superfluidity of ^{3}He. A series of uranium compounds have now been discovered, in which magnetic ordering (with a very small effective magnetic moment $\sim 10^{-2}\mu_B$ per uranium atom) coexists with superconductivity. In two of these compounds—UPt_3 and $U_{1-x}Th_xBe_{13}$—the phase transition into the superconducting state splits into two separate phase transitions. The magnitude of the splitting changes under pressure and with a change in the impurity concentration.

In $U_{1-x}Th_xBe_{13}$ the critical temperature of the transition into the superconducting state depends nonmonotonically on the thorium concentration. After decreasing linearly, $T_c(x)$ undergoes a break and starts to increase rapidly, reaches a maximum, and once again decreases. The line of the second phase transition T_{c2} starts from the break point at $x \approx 1.9\%$ below $T_c(x)$ and merges with T_c at $x \approx 4.3\%$. μSR-experiments show that the superconducting state becomes magnetic for concentrations $1.9 < x < 4.3\%$ (and only in this region) below T_{c2}. On the other hand, in pure UBe_{13} a number of thermodynamic and kinetic quantities have been observed experimentally to exhibit a power-law behavior: the heat capacity, the thermal conductivity, the ultrasonic absorption coefficient, and the London penetration depth. The upper critical field in UBe_{13} is an order of magnitude higher than the paramagnetic limit, and there is no field-dependent Knight shift, either in pure or thorium-doped UBe_{13}. These data indicate that in this substance we are most likely dealing with superconductivity with an unusual type of pairing, similar to that occurring in superfluid ^{3}He. In Ref. 1, on which the report made at the scientific session of the Division of General Physics and Astronomy was based, Makhlin and Mineev propose for the superconducting state a model which explains the properties enumerated above.

For thorium concentrations $0 < x < 1.9\%$ and $x > 4.3\%$ the superconducting state can be one of five phases with either spin-singlet or spin-triplet pairing (the latter possibility was not considered in Ref. 1) and transforming according to the irreducible representations of the cubic group (the symmetry group of UBe_{13} is O_h) A_{2g}, E_g, F_{1g}, F_{1g}, and F_{2g} (singlet case) or A_{2u}, E_u, F_{1u}, F_{1u}, and F_{2u} (triplet case) with the corresponding symmetry groups of the superconducting state $O(T)\times R$, $D_4^{(1)}(D_2)\times R$, $D_3(C_3)\times R$, $D_4(C_4)\times R$, $D_4^{(2)}(B_2)\times R$ (the notation of Ref. 2 is employed).

For triplet phases the gap in the excitation spectrum of the indicated phases vanishes at isolated points on the Fermi surface while for singlet phases the gap vanishes along lines lying on the Fermi surface; this results in a power-law behavior of the thermodynamic and kinetic quantities in the limit $T \to 0$. The isotropy of the properties of UBe_{13} makes it possible to give preference to the phases which transform according to the one-dimensional nontrivial representations A_{2g} and A_{2u}, in which the distribution of the zeros is virtually isotropic. The phase A_{2u} also gives rise to the observed low-temperature behavior of the heat capacity $C(T) \sim T^3$.

For the concentrations $1.9 < x < 4.3\%$, spin-singlet pairing, referring to the identical representation of the cubic group, occurs between the lines $T_c(x)$ and T_{c2}. It has been shown that for such a state inelastic scattering of electrons by impurity centers can cause T_c to increase with the impurity concentration. Conversely, the superconducting state, belonging to a nontrivial representation, is always suppressed by both elastic and inelastic scattering by impurities. Thus the nonmonotonic behavior of $T_c(x)$ in $U_{1-x}Th_xBe_{13}$ is explained under the assumption that the superconducting state in this substance is formed as a result of competition between different superconducting phases with close critical temperatures and belonging to identical and nontrivial representations of the cubic group. The question of the microscopic nature of inelastic scattering remains open.

Finally, for concentrations $1.9 < x < 4.3\%$ a magnetic superconducting phase, consisting of a mixture of the singlet phase, belonging to the identical representation of the cubic group and one of the 10 indicated phases, belonging to the nontrivial representations of the cubic group, is realized below the temperature of the second transition T_{c2}. Magnetism arises as a consequence of the noninvariance of this superconducting state under time reversal. The magnetic

 0038-5670/92/080715-02$03.00

fields measured by the μSR method are concentrated around thorium impurities.

In the case of a mixture of the singlet phase, transforming according to the identical representation, and one of the five phases with triplet pairing, the superconducting state formed also does not exhibit spatial parity. The latter circumstance is possible in $U_{1-x}Th_xBe_{13}$ crystals, though pure UBe_{13} has a center of inversion. The paramagnetic limit and the Knight shift in UBe_{13} are, naturally, absent in the triplet phases. This possibility also exists in the case of singlet phases, since the frequency renormalization of the effective mass, which makes the electrons "heavy," can in many cases affect the heat capacity, but does not change the Pauli magnetic susceptibility, which is determined by the usual "light" electron mass. The high magnetic susceptibility of UBe_{13}, in this case, could be mainly of van-Vleck origin.

I thank N. E. Alekseevskiĭ and A. S. Borovik-Romanov as well as all discussion participants.

[1]Yu. G. Makhlin and V. P. Mineev, Low Temp. Phys. **86**, 49 (1992).
[2]G. E. Volovik and L. P. Gor'kov, Zh. Eksp. Teor. Fiz. **88**, 1412 (1985) [Sov. Phys. JETP **61**, 843 (1985)].

Translated by M. E. Alferieff