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From the Current Literature

SOME NEW DATA ON THE SUPERCONDUCTING PROPERTIES OF METALLIC URANIUM

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As is well known, the temperature of transition into the superconducting state depends on the mass of the isotope:

$$T_c \sim M^{\alpha}, \tag{1}$$

where the approximate value of α for simple metals is -0.5. Such a dependence of the critical temperature on the isotope mass indicates that the lattice vibrations play a principal role in the superconductivity phenomenon. Indeed, the critical temperature, in accordance with the simplest BCS model, is described by the expression

$$T_c = \bar{\omega} e^{-1/g}, \tag{2}$$

where g is a dimensionless interaction constant and $\bar{\omega}$ is the average interaction energy characterizing the region near the Fermi surface where the electrons are attracted to one another. If the mechanism leading to the electron pairing is electron-phonon interaction, then the dimension of the region in which this interaction is attractive is precisely the Debye energy ω_D. Therefore

$$T_c \sim \omega_D \sim \frac{1}{\sqrt{M}}. \tag{3}$$

As seen from formula (2), the critical temperatures of metals whose superconductivity is due to electron-phonon interaction cannot exceed $T_c \sim \omega_D e^{-(2-3)}$. (We take into account here the fact that the interaction constant is usually smaller than $1/2$.) For ordinary metals, these temperatures are of the order of 1–20°K. A much higher transition temperature might exist in superconductors with an electron-electron pairing mechanism, where the characteristic energies $\bar{\omega}$ are of the order of the Fermi energy.*

Unfortunately, the mathematical difficulties arising in the calculation of the electronic properties of real metallic systems have not yet made it possible to obtain a rigorously quantitative criterion of superconductivity even for the usual electron-phonon attraction mechanism. The theoretical problem is all the more complicated in the case of the electron-electron pairing mechanism, where, in essence, there is no small parameter at all. The situation would be greatly simplified were we to have at our disposal at least one superconductor, albeit with a low critical temperature, with respect to which we could categorically state that the main mechanism responsible for its superconductivity is the electron-electron and not the electron-phonon interaction. This would enable us to investigate experimentally the influence exerted on such a superconductor by various factors such as the free-carrier density, pressure, impurities, etc., and this would serve as a good check on various models of the phononless superconductivity mechanism. In this connection, great interest attaches to a study of the superconducting properties of metals that exhibit an unusual behavior with respect to the electron-phonon interaction, and in which we can therefore assume the existence of a phononless attraction mechanism. One such "unusual" superconductor is metallic uranium, the superconducting properties of which apparently do not fit the scheme of the simplest models with electron-phonon attraction mechanism.

There are three known crystalline modifications of metallic uranium[2]; α-U, which has an orthorhombic lattice and is stable at low temperatures, β-U with a complicated cubic or rhombic structure and stable at temperatures from 662° to 772°C, and γ-U, with a body-centered cubic lattice and stable from 772°C to the melting point at 1132°C. The two high-temperature modifications β and γ, can be stabilized by impurities down to very low temperatures, and exhibit transitions into the superconducting state. The critical temperature of β uranium stabilized with 2% Rh or Pt is 0.8°K[3]. The critical temperature of γ-U stabilized with 15% Mo is 2.1°K. Investigations have shown that the superconducting properties of uranium in the β and γ phases differ little from the properties of ordinary superconductors with electron-phonon pairing. In particular, their critical temperature is changed little by variation of the pressure from 0 to 10 kbar, namely

$$\frac{dT_c}{dP} \cong (2-3)\cdot 10^{-5}\,\frac{\text{deg}}{\text{bar}}$$

for β-U and

$$\frac{dT_c}{dP} \cong 0.9\cdot 10^{-5}\,\frac{\text{deg}}{\text{bar}}$$

for γ-U; we note that for lead, for example, this ratio is

$$\frac{dT_c}{dP} = -4.14\cdot 10^{-5}\,\frac{\text{deg}}{\text{bar}}.$$

Measurement[4] of the isotopic effect in γ-U using the isotopes U^{235} and U^{238} has shown that $\alpha(T_c \sim M^{\alpha})$ is very close to -0.5 ($\alpha = -0.53 \pm 0.02$).

The situation with the α modification of uranium is quite different. Recent thorough studies of the superconducting properties of α-uranium[5-8] have shown that this material has a number of features unique to this material only, and that these features cannot be described within the framework of the ordinary models with electron-phonon interaction. Measurements of the specific heat[7] have established that α-U at atmospheric pressure does not become superconducting down to ~0.1°K. When the pressure is increased to only 11 kbar, the critical temperature of α-U increases to 2.2°K, without being accompanied by any changes in the

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*The question of the increased critical temperature for nonphonon attraction mechanism is considered in detail in the reviews of B. T. Geĭlikman and V. L. Ginzburg, published in Usp. Fiz. Nauk [1].

lattice structure. The maximum increase of critical temperature with increasing pressure has heretofore been observed only for Tl,[9] but this increase is smaller by two orders of magnitude than in α-U. Recently a group of American physicists, including the well known superconductivity specialist B. Matthias, measured the isotopic effect in α-U[8]. The measurements were made on the isotopes U^{235} and U^{238}. The metallic samples prepared from these isotopes had very high purity, the impurity content not exceeding 0.0001%. The measurements were made on 10 samples (5 each of U^{235} and U^{238}) at 11 kbar pressure. The measurements have established that the isotopic effect in α-U differs radically from the predictions of the ordinary BCS theory. The exponent α in (1), first, is positive, i.e., the critical temperature of the heavier isotope is higher; second, it is very large:

$$T_c \sim M^{2,2}.$$

In the opinion of the authors of the cited paper, the presence of such an isotopic effect cannot be reconciled in any way with the electron phonon pairing mechanism, and this fact proves that the mechanism responsible for the superconductivity of α-U is electron-electron interaction due to the presence of an unfilled f-shell in uranium. The possibility of such an interaction mechanism in uranium and lanthanum was proposed also earlier[10,11] but according to the calculations there should be no isotopic effect at all in the presence of such an interaction. It should be noted that, as shown by Garland[12] and Swihart[13], the isotopic effect in transition metals may deviate greatly from $\alpha = -0.5$, even in the case of electron-phonon pairing. The strong influence of the Coulomb interaction, owing to the presence of narrow unfilled d-bands, may greatly decrease α and even lead, as indicated by these authors, to a positive value $\alpha = 0.15$ for Ru. On the other hand, such calculations cannot explain the large value $\alpha = 2.2$ obtained for uranium. Summarizing all the foregoing, we can state that the observed superconducting properties of uranium cannot be adequately described at present within the framework of the existing models. Nor is the main cause of such an unusual behavior of superconducting uranium clear. There is still no answer to the question whether it is the result of singularities of the band structure of uranium, connected with the intersection of three closely-lying levels of uranium (7s, 6d, 5f), or with some phononless pairing mechanism.

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