The fact that the coefficients $f_1e^{i\varphi_0}$ and $f_2e^{i\varphi_1}$ are complex leads to an asymmetry in the angular distribution of the positrons with respect to the plane defined by **n**. The difference in the number of decays with the emission of positrons upwards and downwards referred to the interval of effective mass of the two $\pi$ mesons is given by the expression

$$\frac{d(N_{\uparrow}-N_{\downarrow})}{dQ} = \frac{f_1f_2G^2\sin(\varphi_0-\varphi_1)}{2^8\pi^4 7!!}\left(1-\frac{4m^2}{Q^2}\right)(M-Q)^6\left(1+\frac{6Q}{M}\right), \quad (3)$$

where m is the mass of the $\pi$ meson, M is the mass of the K meson, and $Q = [(E_1+E_2)^2 - (\mathbf{K}_1+\mathbf{K}_2)^2]^{1/2}$ is the effective mass of the $\pi$-meson. The phases $\varphi_0$ and $\varphi_1$ depend only on the energy and the center of mass of the $\pi$ mesons, i.e., the quantity Q.

The obtained distribution can be used to find the phase shift for $\pi\pi$-scattering in the energy range $2m \le Q \le M$ if the quantities $f_1$ and $f_2$ are known. The latter can be determined from other correlations in $K_{e4}$ decay, for example, from the effective mass spectrum for the two $\pi$ mesons[4] or the energy spectrum of the electrons.[7]

It follows from (3) that experimental observation of the asymmetry is possible if the phases of the $\pi\pi$-scattering are different in the S and P states and if the contributions of these states are not small.

Thus, the correlations in the $K_{e4}$ decay can yield information on the $\pi\pi$-interaction. There is one other possibility of obtaining information on strong interactions from this decay, specifically the $\pi$K interaction; this has been recently pointed out by Nguen Van Hieu.[12]

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[1] Koller, Taylor, Huetter, and Stamer, Phys. Rev. Letters **9**, 328 (1962).

[2] K. Chadan and S. Oneda, Phys. Rev. **119**, 1126 (1960).

[3] G. Chioccetti, Nuovo cimento **25**, 385 (1962).

[4] L. B. Okun' and E. P. Shabalin, JETP **37**, 1775 (1959), Soviet Phys. JETP **10**, 1252 (1960).

[5] K. Chadan and S. Oneda, Phys. Rev. Letters **3**, 292 (1959).

[6] V. S. Mathur, Nuovo cimento **14**, 1322 (1959).

[7] E. P. Shabalin, JETP **39**, 345 (1960), Soviet Phys. JETP **12**, 245 (1961).

[8] M. Gell-Mann, Proc. Rochester Conf. 1956, ch. 8, p. 25.

[9] L. B. Okun', JETP **34**, 469 (1958), Soviet Phys. JETP **7**, 322 (1958).

[10] Okubo, Marshak, Sudarshan, Teutsch, and Weinberg, Phys. Rev. **112**, 665 (1958).

[11] E. Fermi, Nuovo cimento **2**, Suppl., 1, 17 (1955).

[12] Nguen Van Hieu, preprint.

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## *AN ESTIMATE OF THE LIMITING VALUES OF THE CRITICAL FIELDS FOR HARD SUPERCONDUCTORS*

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VERY high critical fields ($\approx 10^5$ G) have recently been reported for several superconductors.[1] In the present note we give an estimate of the order of magnitude of the upper limit of the critical magnetic field in the case of weak current. A similar estimate was obtained by Clogston.[2] Clogston assumed that the maximum field is governed by the condition that the energy in the magnetic field of electron spins forming a Cooper pair is comparable with the binding energy of the pair

$$\mu H \sim T_c, \quad (1)$$

where $\mu$ is Bohr magneton. This mechanism does not allow for the fact that the superconductors which we are discussing here are always superconducting alloys. The high value of the critical field for such alloys is possible only due to the short mean free path of electrons. A field of the order of that given in Eq. (1) is obtained if we assume that the mean free path becomes comparable with the interatomic distances.

We shall consider first the situation in pure superconductors. The majority of known superconductors undergoes a transition of the first kind to the normal state at some critical value of the magnetic field equal, according to the theory of Bardeen, Cooper, and Schrieffer[3] (at T = 0), to

$$H_c = (T_c/\hbar\gamma)\sqrt{2\pi m p_F/\hbar} \quad (\gamma = 1.78). \quad (2)$$

Then $\mu H_c$ is of the order

$$\mu H_c \sim T_c \sqrt{\frac{v_F}{c} \frac{e^2}{\hbar c}} \ll T_c.$$

As shown by the present author,[4] this situation occurs only in metals of the "Pippard" type for which the depth of penetration in a weak field is $\delta_P \ll \xi_0 = \hbar v_F / T_c$. Metals of "London" type transform from the normal to the superconducting state by a phase transition of the second kind in a field $H_{c2} > H_c$, where

$$H_{c2} \sim H_c \delta_L / \xi_0, \qquad \delta_L^{-1} = \sqrt{4\pi N e^2 / mc^2},$$

$\delta_L$ is the "London" depth of penetration $(\delta_L > \xi_0)$. (At the moment of the transition there is no Meissner effect. For metals of "Pippard" type the field is $H_{c2} < H_c$ and has the meaning of the supercooling field.)

Substituting Eq. (2) we find the critical field for pure "London" superconductors (among which are obviously[4] such materials as pure La, V, Nb, Ta and others, which do not obey the Rutgers formula):

$$\mu H_{c2} \sim T_c (T_c / \varepsilon_F) \ll T_c.$$

Thus also in these pure superconductors the critical field never exceeds $10^2$—$10^3$ G.

The situation is different in superconducting alloys. The present author[5] showed that for alloys with an electron mean free path $l \ll \delta_P$ (i.e., a path which is small compared with the depth of penetration in a weak field) we have:

$$H_{c2} \sim H_c \delta_L / l.$$

The transition in a magnetic field in alloys is always of the second kind.

To make our estimate we shall use the expression for the field $H_{c2}$ at $T = 0$ obtained by Shapoval[6]:

$$H_{c2} = 1.5\, cT_c / elv_F, \qquad \mu H_{c2} = 1.5 T_c (\hbar / p_F l). \tag{3}$$

The validity of the above formulas is limited to the region $p_F l \gg \hbar$, i.e., to defect concentrations for which the mean free path $l$ is large compared with the interatomic distances $a \approx \hbar / p_F$. To estimate the upper limit of the critical field in alloys we shall assume that $\hbar / p_F l \approx 1$, whence we obtain, using Eq. (1), $H_{c\,max} \approx 10^4 T^0$ G. We emphasize once more that such high fields ($\approx 10^5$ G) can in principle occur only in alloys. The less careful the preparation of these alloys the higher the critical field. The electron mean free path or the residual resistance of a sample can be used as a measure of its critical field. In particular for relatively low defect concentrations Eq. (3) can be rewritten in the form[6]

$$H_{c2} = \frac{3}{2\pi} \frac{ec\gamma T_c}{\sigma k},$$

where $\gamma$ is the coefficient in the linear law for the electronic specific heat of a unit volume and $\sigma$ is the conductivity. When the mean free path becomes comparable with the atomic distances we reach the upper limit of the critical field for alloys. As far as the author is aware the conductivity of such alloys has not been measured. It would be interesting to investigate in what region the law of proportionality of the critical field and the residual resistance is valid. If we had a graph of the dependence of $H_c$ on $\rho = \sigma^{-1}$, which should be a curve with saturation, we could quite accurately predict the upper limit of the critical magnetic field for superconducting alloys.


[1] J. E. Kunzler, J. Appl. Phys. **33**, 1042 (1962); Berlincourt, Hake, and Leslie, Phys. Rev. Lett. **6**, 671 (1961).

[2] A. M. Clogston, Phys. Rev. Lett. **9**, 266 (1962).

[3] Bardeen, Cooper, and Schrieffer, Phys. Rev. **106**, 162 (1957).

[4] L. P. Gor'kov, JETP **37**, 833 (1959), Soviet Phys. JETP **10**, 593 (1960).

[5] L. P. Gor'kov, JETP **37**, 1407 (1959), Soviet Phys. JETP **10**, 998 (1960).

[6] E. A. Shapoval, JETP **41**, 877 (1961), Soviet Phys. JETP **14**, 628 (1962).


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## *ABSORPTION OF SOUND IN LIQUID He II BELOW 0.6°K*

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WOODRUFF[1] and Dransfeld[2] made an attempt to explain the absorption of sound in superfluid He II at temperatures below 0.6°K. At such low temperatures we are dealing with a special case. On one hand the mean free path of phonons is considerably greater than the wavelength of sound, but on the other the energy of the sound quanta $\hbar\omega$ is still