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Magnetic Field Penetration Depth in the Heavy-Electron Superconductor UBe₁₃

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We report the observation of a T^2 temperature dependence of the magnetic field penetration depth in UBe₁₃ at low temperatures. We show that this behavior is consistent with an anisotropic gap function for an axial p -wave state. Our results further show that the Landau parameter F_1^{\uparrow} appears to be small.

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The heavy-electron superconductor UBe₁₃ shows anomalous, i.e., non-BCS, behavior in several properties like the electronic specific heat,¹ ultrasonic attenuation,² and spin-lattice relaxation.³ These properties are directly related to the spectrum of quasiparticle states that can be excited from the superconducting ground state, and it has been argued that they are more consistent with the spectrum expected for a spin-triplet, or odd-parity, paired state. Among experiments yielding more direct information about such an unconventional superconducting ground state are those which investigate the supercurrent properties, such as Josephson effects and magnetic field penetration. The former are particularly sensitive to the symmetry properties of the ground-state wave function. Partly as a result of material preparation difficulties, however, they have not yet yielded clear-cut answers in the case of UBe₁₃.⁴ This Letter describes principal results on the latter experiments in which we have observed and calculated the magnetic field penetration depth in UBe₁₃ as a function of temperature. The details of this work will be published elsewhere.⁵

By inspecting the basic London equation

$$\mathbf{j}^s = - (c/4\pi)\lambda^{-2}\mathbf{A}, \quad \lambda^2 = (m^*c^2/4\pi e^2)m/\rho^s, \quad (1)$$

which relates the supercurrent density \mathbf{j}^s to the magnetic vector potential \mathbf{A} and defines a field penetration depth λ , one sees that by measuring $\lambda(T)$ one can get information about the following quantities and properties of the superconductor: (i) the value of the effective mass m^* , (ii) the temperature dependence of the superfluid mass density ρ^s , and (iii) (as will be shown below) the possible importance of Fermi-liquid effects

and the value of the Landau parameter F_1^{\uparrow} . In what follows, we show that our measurements yield information on each of these points.

We obtained internally consistent data on four samples of UBe₁₃, and present here the results for one of them. Its characteristics were as follows: density $\rho = 4.3 \text{ g/cm}^3$, $T_c = 0.86 \text{ K}$, 10%–90% transition width = 0.06 K, Meissner effect (in $H = 0.3 \text{ Oe}$) = 3.5%. The experiment consisted of observation of the reversible changes in magnetization with temperature of the superconducting sample which was located inside one coil of a sensitive SQUID bridge circuit.⁶ These reversible changes, which must be due to the field penetration effect only (for a more detailed discussion of this point see Ref. 5), were nearly independent of whether the measuring field (always less than 0.3 Oe) was switched on either above or below T_c . From them the changes in the penetration depth $\lambda(T) - \lambda(T_{\min})$, with T_{\min} the lowest measuring temperature, can be calculated in a straightforward manner. In Fig. 1 we show these observed changes, plotted versus $(T/T_c)^2$ for both the UBe₁₃ sample as well as for a reference sample of Sn.

The most striking feature of Fig. 1 is that the temperature variation of $\lambda(T)$ for UBe₁₃ is quite unlike that of Sn, a well-known BCS superconductor. In fact, UBe₁₃ shows a T^{κ} variation of $\lambda(T) - \lambda(0)$, with a temperature exponent $\kappa \approx 2$ (see below), inconsistent with the exponential behavior $\sim (\Delta_0/kT)^{1/2} \times \exp(-\Delta_0/kT)$ expected for an isotropic London superconductor. The tin data are, over a significant range of temperature, well represented by $\lambda(T) - \lambda(0) = \lambda(0) \{ [1 - (T/T_c)^4]^{-1/2} - 1 \}$, as would be expected for a nonlocal BCS superconductor with near-

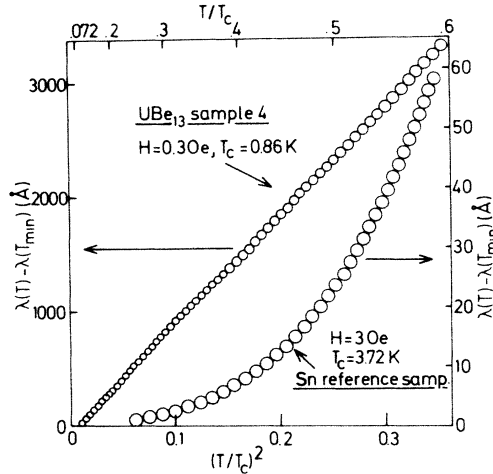


FIG. 1. Incremental magnetic field penetration depth $\lambda(T) - \lambda(T_{\min})$ of UBe_{13} as a function of $(T/T_c)^2$ (left scale). The size of the circles shows the experimental uncertainty. Also shown, for comparison, are the data for the Sn reference sample (right scale).

ly isotropic energy gap. Fitting the data by this function, we find for tin $\lambda(0) = 460 \text{ \AA}$, in agreement with earlier work.⁷

Before further discussing the UBe_{13} data, we outline now a calculation of the temperature dependence of the penetration depth. There are two possible physical origins for a power-law behavior of the penetration depth and hence the superfluid density: *First*, if the gap function of the superconductor under consideration has zeros somewhere on the Fermi surface, for example point or line nodes, then the number of thermal excitations vanishes at low temperatures according to a power law $(kT/\Delta_0)^\kappa$ with some temperature exponent κ . A well-known example for a pair-correlated system with a gap with point nodes is the p -wave superfluid $^3\text{He-A}$ with a spin-fluctuation exchange mechanism replacing the usual electron-phonon pairing mechanism. *Second*, it has been shown that the addition of magnet-

ic impurities to an ordinary (s wave) superconductor or nonmagnetic impurities to a p -wave superconductor results in a T^2 behavior of the magnetic penetration depth as well as in a linear low-temperature specific heat and a reduced specific-heat jump in the so-called gapless regime or dirty limit.^{5,8} Gapless superconductivity as an explanation of the observed T^2 law in the penetration depth may be ruled out, however, by the observation of a T^3 temperature dependence of the specific heat and a large specific-heat discontinuity.¹

We have therefore reconsidered the theory of the electromagnetic response in a p -wave superconductor with uniaxially anisotropic gap of the form

$$\Delta(\mathbf{k}, T) = \Delta_0(T) f(\hat{\mathbf{k}} \cdot \hat{\mathbf{l}}), \quad (2)$$

with $\hat{\mathbf{l}}$ (unit vector) the axis of gap symmetry, Δ_0 the temperature-dependent maximum of the gap, and f some function of $\hat{\mathbf{k}} \cdot \hat{\mathbf{l}}$ with nodes which will be specified later.

For a superconductor described by the general class of gap functions (2), restricted to a half space $z \geq 0$, and exposed to an external field \mathbf{h}^{ext} in the x - y plane, one sees that the London equation (1) has to be generalized in that the superfluid density ρ^s and the penetration depth λ have to be replaced by appropriate tensor quantities. The superfluid density tensor is characterized by the two eigenvalues ρ_{\parallel}^s and ρ_{\perp}^s according to the principal axes parallel and perpendicular to the vector $\hat{\mathbf{l}}$ of gap symmetry. The shielding current \mathbf{j}^s can then be shown to be purely transverse, if one properly accounts for the order-parameter collective modes within the framework of hydrodynamic theory (for details see Ref. 5 and Millis⁹). In particular, if we assume the gap orbital degrees of freedom (here represented by $\hat{\mathbf{l}}$) to be strongly pinned, only the contribution from the phase gradient of the order parameter is important. For homogeneous $\hat{\mathbf{l}}$, the Fourier component of the current is then given by the following generalization of Eq. (1) to anisotropic superconductors:

$$\mathbf{j}_{\mu}^s(\mathbf{q}) = - (e^2/mc) [\rho^s - (\hat{\mathbf{q}} \cdot \rho^s \cdot \hat{\mathbf{q}}) / (\hat{\mathbf{q}} \cdot \rho^s \cdot \hat{\mathbf{q}})]_{\mu\nu} A_{\nu}(\mathbf{q}). \quad (3)$$

For arbitrary directions of $\hat{\mathbf{l}}$, the current is not parallel to the vector potential. This is reflected in a penetration depth tensor which has eigenvalues λ_1 and λ_2 with respect to the directions parallel and perpendicular to the projection $\hat{\mathbf{L}}$ of the vector $\hat{\mathbf{l}}$ into the x - y plane; they are related to ρ_{\parallel}^s and ρ_{\perp}^s as follows:

$$\lambda_1^2 = \lambda^2(0) \rho / \rho_{\perp}^s, \quad \lambda_2^2 = \lambda^2(0) (\rho / \rho_{\parallel}^s) [1 - \hat{l}_z^2 + (\rho_{\parallel}^s / \rho_{\perp}^s) \hat{l}_z^2], \quad (4)$$

where \hat{l}_z is the z component of the vector $\hat{\mathbf{l}}$ and $\lambda(0)$ is the penetration depth at zero temperature. The local magnetic field $\mathbf{h}(z)$ inside the superconductor is finally obtained in terms of the external field $\mathbf{h}(0) = \mathbf{H}^{\text{ext}}$, the penetration depths λ_1 and λ_2 , and the directions $\hat{\mathbf{L}}$ and $\hat{\mathbf{z}} \times \hat{\mathbf{L}}$ as

$$\mathbf{h}(z) = \hat{\mathbf{L}} (\hat{\mathbf{L}} \cdot \mathbf{H}^{\text{ext}}) \exp(-z/\lambda_1) + \hat{\mathbf{z}} \times \hat{\mathbf{L}} (\hat{\mathbf{z}} \times \hat{\mathbf{L}} \cdot \mathbf{H}^{\text{ext}}) \exp(-z/\lambda_2). \quad (5)$$

Low-temperature results.—The explicit form of $\rho_{\parallel, \perp}^s$ becomes particularly simple at very low temperatures if one specializes Eq. (2) to the axial state with $f(\hat{\mathbf{k}} \cdot \hat{\mathbf{l}}) = |\hat{\mathbf{k}} \times \hat{\mathbf{l}}|$ (two point nodes) and to the polar state with

$f(\hat{\mathbf{k}} \cdot \hat{\mathbf{i}}) = \hat{\mathbf{k}} \cdot \hat{\mathbf{i}}$ (equatorial line of nodes) for which one obtains in the absence of Fermi-liquid effects

$$\lim_{T \rightarrow 0} \rho_{\parallel, \perp}^s / \rho = 1 - a_{\parallel, \perp} (kT/\Delta_0)^{\kappa_{\parallel, \perp}}, \quad (6)$$

where in the axial state $\kappa = 2$ (4) and $a = \pi^2 (7\pi^4/15)$, and in the polar state $\kappa = 3$ (1) and $a = 27\pi\zeta(3)/4$ ($3\pi \ln 2/2$), for the orientations \parallel (\perp).

Gap orientation effects.—It is clear that the predicted penetration depth for a given anisotropic state will depend strongly on the direction of the vector $\hat{\mathbf{i}}$, which may be oriented by crystal electric fields, magnetic fields, superflow, and surfaces.^{5,10} One will therefore generally expect the observed penetration depth to be a mixture of the two eigenvalues of the tensor λ . At very low temperatures, however, the main contribution will originate from the eigenvalue with the lowest temperature exponent κ ; i.e., for the axial state we expect a T^2 law from λ_2 (if $\hat{\mathbf{i}}$ is not exactly perpendicular to \mathbf{A}) and for the polar state the dominating contribution comes from λ_1 , which is linear in T .

Fermi-liquid effects can be easily incorporated in our theory. Their importance is reflected in the explicit occurrence (c.f. Ref. 11) of the interaction parameter F_1^s in the expression for the superfluid density:

$$\rho_{\parallel, \perp}^s = \frac{\rho_{\parallel, \perp}^{s0} (m/m^*) (1 + F_1^s/3)}{1 + F_1^s (1 - \rho_{\parallel, \perp}^{s0}/\rho)/3}, \quad (7)$$

where $\rho_{\parallel, \perp}^{s0}$ are the superfluid densities in the absence of the Fermi-liquid interaction. At zero temperature one is therefore left with a penetration depth renormalized by a factor $[(m^*/m)/(1 + F_1^s/3)]^{1/2}$, which is unity if translational invariance may be assumed. It is not entirely clear, however, to what extent the Galilean-invariance arguments leading to the effective-mass relation $m^*/m = 1 + F_1^s/3$ should be even approximately valid in a system with localized f electrons. Some authors¹² have made use of this relation to discuss the origin of the heavy-electron mass. On the other hand, it has been argued¹³ that the effective mass should scale with F_0^s rather than with F_1^s .

The influence of nonmagnetic impurities on the penetration depth of a p -wave superconductor will be discussed in detail in Ref. 5. Here we only note that the low-temperature power laws expected for an axial p -wave superconductor, in contrast to those for the polar state, remain unaltered in the presence of nonmagnetic impurities of not too large concentration.

Comparison of theory with experiment.—We start our comparison with the experimental data using Eq. (7) with $\lambda(0)$ and F_1^s as adjustable parameters. The temperature-dependent maximum of the gap is interpolated as

$$\Delta_0(T) = \delta_{sc} kT_c \tanh[(\pi/\delta_{sc})(a\Delta C/C_N)^{1/2}(T_c/T - 1)^{1/2}], \quad (8)$$

where we insert $a = \frac{2}{3}$ (1, 2), the weak-coupling values of $\delta_{sc} \equiv \Delta(0)/kT_c = 1.76$ (2.03, 2.46) for the isotropic (axial, polar) state, respectively, and the experimental value¹ for the specific-heat discontinuity $\Delta C/C_N = 2.5$. In Fig. 2 we show attempts to fit the experimental data, plotted as $\lambda(T) - \lambda(T_{\min})$ vs $(T/T_c)^2$, by the theoretical result (4) together with (7). In Fig. 2(a) we plot λ_2 ($\hat{\mathbf{i}} \parallel \mathbf{A}$) for the axial (full lines) and λ_1 ($\hat{\mathbf{i}} \perp \mathbf{A}$) for the polar (dashed lines) state, keeping $\lambda(0) = 4200 \text{ \AA}$ fixed and varying F_1^s as indicated. Also shown in this figure is a curve for the axial state with $F_1^s = 600$ (approximate validity of the effective-mass relation is assumed) and, as a dashed-dotted

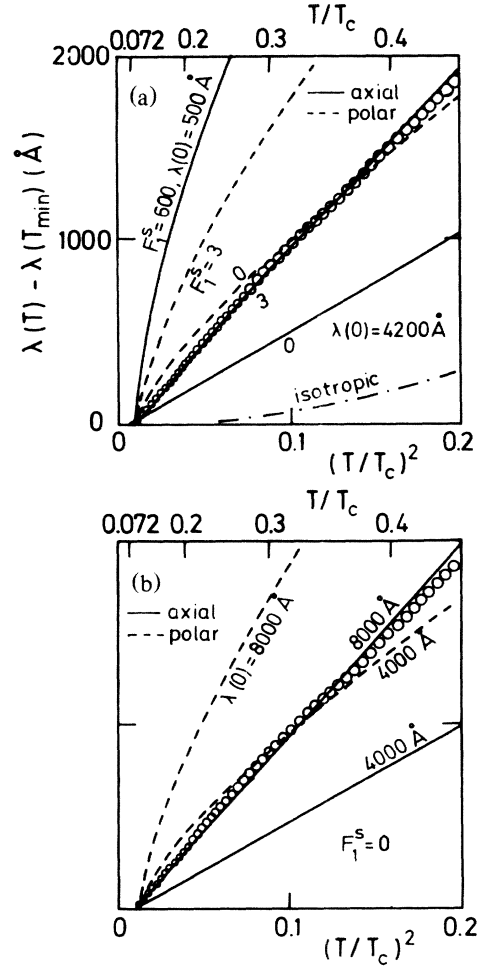


FIG. 2. Comparison of the measured incremental penetration depth $\lambda(T) - \lambda(T_{\min})$ (circles), plotted vs $(T/T_c)^2$, with theory (full lines, axial state; dashed lines, polar state; dashed-dotted line, isotropic state). In (a) we kept $\lambda(0) = 4200 \text{ \AA}$ fixed and varied F_1^s as indicated, whereas (b) was evaluated for two values of $\lambda(0)$ in the absence of Fermi-liquid effects ($F_1^s = 0$). The maximum gap was taken from Eq. (8).

line, the (local limit) result expected for an isotropic superconductor without Fermi-liquid effects. In Fig. 2(b) the penetration depth for the axial (full lines) and the polar (dashed lines) state was evaluated in the absence of Fermi-liquid corrections ($F_1^{\ddagger}=0$) for two values of $\lambda(0)$ as indicated.

It is evident from this figure that the observed T^2 behavior of the London penetration depth is inconsistent with the predictions of BCS theory for a pure, isotropic singlet superconductor. Nor can the temperature dependence be explained by assumption of a gap with a line of nodes (polar state) as the curvature of the dashed lines shows. A gap function with point nodes (axial state), however, allows for a fairly good fit to the experimental data for a certain variety of combinations of the parameters $F_1^{\ddagger} \leq 20$ and $\lambda(0) \leq 8000 \text{ \AA}$. The parameter combinations $\lambda(0) = 4200 \text{ \AA}$ and $F_1^{\ddagger} = 3$ in Fig. 2(a) and $\lambda(0) = 8000 \text{ \AA}$ and $F_1^{\ddagger} = 0$ in Fig. 2(b) are only two examples for such a fit.

It should be emphasized that the penetration depth observed in a real experiment need not correspond directly to one of the eigenvalues of the superfluid density tensor which have been used for the fit. Nevertheless, at low temperatures we expect a T or a T^2 behavior to dominate depending on whether the state possesses line or point nodes, respectively. The axial state thus represents a possible fit to the experimental data, provided that the \hat{I} vector is not fixed exactly perpendicular to the sample surface over a distance large compared to λ . This will always be the case if the magnetic and/or crystal field orienting effects are sufficiently strong.

The experimental data do not appear to be consistent with a large value of the Landau parameter F_1^{\ddagger} and therefore with approximate validity of the Galilean-invariance effective-mass relation (assuming that the crystal mass m is small). This conclusion follows from the observed pure power-law behavior in $\lambda(T) - \lambda(0)$ over a large temperature range. In addition, a fit to the data at the very lowest temperatures with F_1^{\ddagger} large is inconsistent with values of $\lambda(0)$ expected on theoretical⁵ and experimental³ grounds. If confirmed by absolute penetration-depth measurements, this would lend support to those theories of the heavy-fermion normal state¹³ which predict a small F_1^{\ddagger} and scaling of F_1^{\ddagger} with m^*/m based on an unrenormal-

ized compressibility.

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