Two classic experiments in superconductivity

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Two experiments of I. K. Kikoin—the correlation between superconductivity and the galvanomagnetic properties of metals (1933), and the gyromagnetic effect in superconductors (1938)—which were carried out long before the appearance of the microscopic theory of superconductivity, anticipated two of its principal conclusions. Established were: 1) the determining role of electron-phonon interaction; 2) the orbital nature of diamagnetism in superconductors.

In 1988, Isaak Konstantinovich Kikoin (1908–1984) would have been 80 years old. He was an outstanding person, and an outstanding organizer and physicist-experimenter. We will illustrate this, using two of his classic experiments[1–4] as an example.

By the beginning of the 1930s, 10 pure metals were known to become superconductors at sufficiently low ($T > 1.2$K) temperatures (Ti, Ga, Nb, In, Sn, Ta, Hg, Tl, Pb and Th). The natural question arose as to what properties (other than the fact of superconductivity itself) distinguish superconducting metals from other metals at normal (not very low) temperatures. In one hypothesis (Meissner, Lorentz), the superconducting current was associated not with "free" electrons, but with electrons more or less firmly attached to the atoms. (Now we understand that there is "something to it" in this hypothesis: in contemporary language one speaks of weak or strong electron-phonon coupling). I. K. Kikoin proposed,[4] that the "degree of bonding" of electrons in superconducting and normal metals is already different at normal temperatures, and that it is precisely this which distinguishes superconductors from other conductors. Electrons' "freedom to bond" is determined, as is known, by their mobility, which can be expressed as, $R_{\mathrm{H}}\sigma$, where R_{H} is the Hall constant, and σ is electrical conductivity.

For the majority of pure metals, research into the Hall effect and electrical conductivity had already been conducted by that time, although some of the least reliable, or simply not very precise, results had to be rechecked. As a result, a completely new regularity was established: "for superconductors, in contrast to other conductors at normal temperatures, there are significantly lower values for the product $R_{\mathrm{H}}\sigma$, and also for R_{H} itself ". It was demonstrated that the discovered regularity was valid to the same degree, not only for pure metals, but also for metallic alloys (Pb-Bi, Bi-Ti, Sb-Ti) and for a series of compounds of metals and nonmetals. Thus, the established regularity had an entirely general character, and revealed the presence of a "connection between the Hall effect and superconductivity". In fact, this was one of the first (and possibly even the first) experimental evidence of the determining role of the strength of electron-phonon interaction in superconductivity.

The criterion for superconductivity thus determined in this work can be expressed in the form $R_\sigma \lesssim 50$, where R is expressed in cm^3/C, and σ in (ohm·cm)$^{-1}$. It is interesting that in the earlier theoretical works of Frölich[10] and Bardeen,[11] the condition under which superconductivity appeared was also expressed in terms of the electrical resistance of the material (at room temperature). So, in Bardeen's theory, the condition could be approximately written in the form $\sigma/n \lesssim 10^{17}$, where σ is expressed in (ohm·cm)$^{-1}$, and n in cm^{-3}. It is not difficult to be convinced that the two cited criteria coincide with each other!

Yet another work of I. K. Kikoin concerning superconductivity[1-3] goes back to two outstanding experiments of the 20th century—the Einstein–de Haas effect (1916) and the Meissner effect (1933). The particular characteristics of diamagnetism of superconductors which distinguish them from ideal conductors raised a question about the nature of this diamagnetism: was it associated with the spins of the electrons, or was it caused by their orbital motion (that is, by the current). The answer to this question was "very important for the confirmation of the fundamental thought behind the phenomenological theory of F. London and H. London".[5] It was natural to attempt to solve the problem by using those very same direct methods which were used in proving the spin nature of ferromagnetism, namely by means of the direct study of the gyromagnetic effect. However, it was not clear whether the observation of such an effect in superconductors was possible in principle, inasmuch as the absence in them of an interaction of electrons with the lattice should not, it would seem, lead to the appearance of a "recoil" of the sample, as a result of a change in the body's magnetic moment.

"The measurement of the gyromagnetic effect, despite its seeming fundamental simplicity, is in fact an extremely difficult experimental task. This is so even in the instance of measurements of ferromagnetic bodies, the magnetization of which is great, even in comparatively weak external fields. Even greater difficulties arise in the research of the gyromagnetic effect in superconductors, when the magnetization of the test material is approximately 50–100 times less than with ferromagnetics. An additional difficulty comes from the necessity of carrying out the measurements at low temperatures".[3] It was neccesary to choose a method of measurement which would exclude the various side effects.

It is possible to illustrate the methodological complications of the experiment in the following manner. Torque

$$\theta = \frac{1}{g}\frac{2mc}{e}\frac{\mathrm{d}M}{\mathrm{d}t} \sim \frac{1}{g}\frac{2mc}{e\tau}M, \qquad (1)$$

acts (when there is a recoil) on a body with a variable magnetization, where g is the Landé g factor (equal to 1 for orbital angular momentum, and equal to 2 for spin), and τ is the characteristic time for the reversal of the field. In the absence of absolute parallelism of the axis of the cylindrical test material being studied,1) for the field $\mathbf{H}(H_x, \mathrm{O}, H_z)$, its magnetic moment is $\mathbf{M}(M_x, M_y, M_z)$, where $H_x, \sim \alpha H$, M_x,

$M_y \sim \alpha M$, and $\alpha \ll 1$, α being the angle between the axis of the sample and the magnetic field. An incomplete compensation for the magnetic field of the Earth gives $H_y^0 \sim H_T/k$, where $k \gg 1$, k being the coefficient of compensation, and $H_T \sim 1$ Oe, the Earth's magnetic field.

In such a situation, parasitical torques

$$\theta_1 \sim M_y H_x \sim \alpha^2 HM, \quad \theta_2 \sim M_x H_y^0 \sim \frac{\alpha}{k} H_T M \tag{2}$$

appear.

When $\alpha \sim 1'$, $k \sim 10^2$, $H \sim 10^2$ Oe, $\tau \sim 1$s (values characteristic for typical experiments of that time) our result is $\theta_1 \sim \theta_2 \sim 10\theta$, that is, the parasitic effect is substantially greater than the basic effect.

It is therefore clear that it is necessary to choose a research method which would exclude the possibility of ponderomotive side effects. This was successfully accomplished by means of the resonance method, suggested already by Einstein, and carried out by Scherer and Coeterier.[6] The basic idea of the method consists of the following. Forced vibrations in a sample suspended in a solenoid with a periodically reversing field $H = H_0 \sin \omega t$, are described by the equation

$$K\ddot{\varphi} + p\dot{\varphi} + D\varphi = T, \tag{3}$$

where K is the moment of intertia of the test material, p is the damping factor, D is the coefficient of torsion of the suspension thread, and $T = \theta_1 + \theta_2 + \theta$ is the torque. If we allow that $M = M_0 \sin \omega t$, we find that

$$T = \theta_0 \cos \omega t + T' \sin \omega t + T'' \sin^2 \omega t, \tag{4}$$

where

$$\theta_0 = \frac{1}{g}\frac{2mc}{e}\omega M_0, \quad T' = \frac{\alpha}{k} H_T M_0, \quad T'' = \alpha^2 H_0 M_0.$$

If the frequency ω of the reversal of the field coincides with the resonance frequency $\omega_0 = (D/K)^{1/2}$ of the sample vibrations, then it is possible to omit the last term in (4) and the solution to (3) takes the form

$$\varphi = \varphi_0 \cos(\omega_0 t + \gamma), \tag{5}$$

where

$$\gamma = \operatorname{arctg} \frac{\theta_0}{T'}, \quad \varphi_0 = \frac{[(T')^2 + \theta_0^2]^{1/2}}{p\omega_0}.$$

If there is no parasitic torque T' ($T' = 0$), then $\varphi \sim \sin \omega_0 t$, that is, the vibrations are displaced one quarter of a period ($\gamma = \pi/2$) relative to the forcing torque $\theta \sim \cos \omega_0 t$. If, in fact, $T' \neq 0$, then the phase of the sample vibrations at resonance *is* $\gamma \neq \pi/2$.

It is possible, however, also in the latter case, to obtain $\gamma = \pi/2$ artificially, by reversing the field at the moment the sample is passing through the equilibrium point. Then dH/dt attains a maximum value when $\varphi = 0$ independently of the presence or absence of any sort of side effects, and

$$\varphi = \varphi_\infty \sin \omega_0 t,$$

where

$$\varphi_\infty = \frac{\theta_0}{p\omega_0} = \frac{1}{g}\frac{2mc}{e}\frac{\varkappa V H_0}{p}; \tag{6}$$

V is the volume of the sample, and $\varkappa$ is the susceptibility of the sample (taking the demagnetization coefficient into account). The expression (6) then allows one to determine g, by measuring φ_∞, and knowing the remaining quantities that enter into it.

The synchronization of the reversal of the field with the vibrations in the sample indicated above "is realized best of all, if one allows the sample itself to execute the reversal of the field at the correct time".[3]

In this experiment, an installation was used consisting of: 1) a suspension system, 2) a circuit for the automatic reversal of the field of the solenoid, 3) a magnetizing solenoid, 4) a method for the compensation for the Earth's magnetic field, and 5) cryogenic apparatus.

1. The suspension system. A spherical shape of the sample was recognized to be the most advantageous, because in such a case the non-parallelism of the moment of the sample and of the external field is at a minimum. For this reason, a sphere of pure lead (kindly provided by P. L. Kapitsa) with a ≈ 3 mm diameter was used (the maximum variance of the diameter in various directions did not exceed 2–3 μm). Using nitrocellulose varnish, it was glued to the lower end of a glass tube ~ 50 cm in length and 0.12 mm in diameter (the axis of the tube did not deviate from the diameter of the sphere by more than 10 μm). A quartz thread, with a diameter of 10–12 μm and a length of ~ 15 cm, which served as the suspension thread, was glued to the upper end of the tube.

2. The circuit for the automatic reversal of the field. Autoresonance reversing of the field was carried out by means of a special thyratron circuit, which was controlled by a photoelement, on which light fell, that was reflected from a small mirror, attached to the suspension system. In this manner, the field reversed its direction (to the opposite polarity) with the passing of the test material through the equilibrium point.[2)] The gyromagnetic moment occurred only at the moment of the reversing of the field. For the remaining time, it was equal to zero. The phases of parasitic ponderomotive torques proportional to the field coincide with the phase of vibration of the sample itself, and for this reason display no influence on the amplitude of resonance".[3]

3. The magnetizing solenoid. The demands for homogeneity of the field created by the solenoid were sufficiently severe so that a special construction was used, which allowed elimination of all the (radial) derivatives of the field up to the sixth.

4. Compensation for the Earth's field was carried out by means of Helmholtz coils with a 1200 mm diameter, between which the entire installation was situated. A compensation coefficient of $k = 330$ was achieved, which corresponded to a residual field of $\sim 5 \cdot 10^{-4}$ Oe.

Careful orientation and adjustment of the installation provided measurements of great accuracy, as a result of which it was established that the Landé g factor for superconductors was equal to

$$g = 1 \pm 0.03.$$

This is "a value which corresponds to the fact that magnetization was caused by closed orbits. The Landé g factor turned out to be negative, corresponding to the negatively charged carriers of the magnetization (the electrons)".

"The numerical value obtained for the Landé g factor indicates that magnetization of superconductors is in any case caused, not by electron spin, but by closed electron currents".

When calculating g using formula (6), the free electron mass (and not the effective mass) was used for the quality m. An exact proof of this was later given by Broer[7] (see also Ref. 8).

The work of I. K. Kikoin, in essence, completely solved the problem which had been posed. Only one other investigation,[12] carried out 14 years later, is known, the authors of which supposed (apparently through a misunderstanding), that "the work of Kikoin and Gubar is not totally clear regarding the sign of the effect". They reproduced in full the methodology of Kikoin's experiment, and confirmed his conclusions.

Analysing the results of Ref. 2 Meissner[13] explained them in the following manner: "The magnetic field penetrates (into the superconductor) only to a small depth, but at its reversal, an electric field appears, which acts both upon the superconducting electrons and upon positive ions (of the lattice). Inasmuch as the superconducting electrons do not drag the ions after themselves, these two systems move independently with equal and opposing angular momenta. It is precisely the movement of the positive ions which is observed in the experiment."

It is interesting that the inverse gyromagnetic effect (an analog of the Barnett effect) in superconductors, consisting of the creation of a magnetic moment in a rapidly rotating superconductor, has not been registered to date, although attempts to do just that have been made.[9]

[1] In all known experiments of that time, the sample took the form of a cylinder.

[2] In this instance, the value H_0 in formula (8) is the amplitude of the first harmonic of the field strength.

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