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The Meissner and para-Meissner effect in superconductors

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ABSTRACT:

Occurrence of superconductivity and Meissner effect is reviewed. Meissner effect shows that superconductors exhibit diamagnetic property. It has been reported by several researchers that paramagnetic property of certain high T_c superconductors appears spontaneously in field cooling (FC) condition well below H_{c1} . A critical field H_0 is predicted from the expression of free energy of the single current loop consisting of a single Josephson junction. For $H > H_0$ there is Meissner effect and for $H < H_0$ para-Meissner effect (PME) occurs. This leads to the minimum observable flux quantum as $\frac{\phi_0}{4}$.

KEYWORDS: Meissner effect, para-Meissner effect, flux quantum.

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INTRODUCTION:

The phenomenon of superconductivity was first observed by Kamerlingh Onnes[1] in 1911, when he found that resistance of mercury dropped abruptly to a value experimentally undetectable at a temperature about 4.2K. The temperature at which it occurs is called superconducting transition temperature (T_c).

This transition temperature (T_c) depends on the applied magnetic field. If the applied magnetic field is increased to a certain value H_c, known as critical field for the sample then the superconductor is driven to its normal state. The critical field is approximately related to the temperature by the relation

$$H_c = H_0 \left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

where H_0 is the critical field at absolute zero temperature. This T_c and H_c vary from metal to metal. In fact majority of superconductors are not pure elements but alloys and compounds.

For many years the T_c of niobium-tin alloy was the highest with $T_c = 18.1$ K. In 1973 it was discovered that the film made out of compound Nb_3Ge become superconducting at $T_c = 22.3$ K. In 1986 Bednorz and Muller[2] reported that La-Ba-Cu-O system began its superconducting transition as it is cooled below 35K. All of the subsequent work proved that there were high temperature superconductors. The highest transition temperature known today for this series of compounds is 203K.

MEISSNER EFFECT:

In 1933, Meissner and Ochsenfeld[3] found that when a superconducting specimen is cooled below its T_c, either in a magnetic field or not, the specimen never allows a magnetic flux density to exist in its interior. This phenomenon is called the Meissner effect.

So, according to this effect inside a superconductor we always have, $B = 0$, where B is the magnetic flux density. Now we have the relation

$$B = H_a + 4\pi M$$

Where H_a is the applied magnetic field and M is the magnetization. Inside the superconductor $B = 0$, so, $H_a = -4\pi M$

Hence the susceptibility, $\chi = \frac{M}{H_a} = -\frac{1}{4\pi}$

Thus we see that superconductor shows the property of perfect diamagnetism. Pure specimen of many material shows complete Meissner effect. That means below T_c flux inside the superconductor is zero. Thus there is only one value of H_c available for a particular temperature T ($T<T_c$). These materials are called Type – I superconductors.

Transition metals and alloys shows different behavior. There are two critical fields H_{c1} and H_{c2} available for a particular temperature T ($T<T_c$). Between H_{c1} and H_{c2} Meissner effect is said to be incomplete, the specimen is threaded by magnetic flux lines, these are called vortices. These superconductors are known as Type - II superconductors. Here one point can be noted that all high T_c superconductors are Type – II superconductors.

PARA-MEISSNER EFFECT:

The field cooling Meissner effect of some ceramic high T_c samples was reported[4] to remain incomplete at $H << H_{c1}$. The flux expulsion for these samples is of the order of 1/3 of a zero field cooling sample. This incompleteness was explained by flux pinning and anisotropy of the London penetration depth. It is quite common to find values less than $-1/4\pi$ due to imperfection in the samples. It came as surprise when Braunisch et al[5] and Shrivastava[6] reported that in certain Bi-based high – T_c superconductor a paramagnetic magnetization appear at a low magnetic field $H<H_{c1}$ in field cooling (FC) condition at a temperature well below T_c . Since this magnetization occurs spontaneously, this effect is named as para- Meissner effect (PME).

It was reported that the surface microstructure plays a key role for PME[7]. If the phase of the Josephson current is shifted by π, it gives rise to the change in sign of the free energy and hence it may provide the explanation for the change in sign of the magnetization[8]. We consider a superconducting current loop consisting of a single Josephson junction with inductance L and current density J then the free energy of the loop[9] is given by

$$\in = \frac{1}{2}LJ^2 - \frac{J\,\phi_0}{2\pi}\,cos\left[\frac{2\pi}{\phi_0}(\phi + LJ)\right]$$

Where ϕ_0 is the flux quantum. The magnetic field arises in the above due to the flux quantization, $\phi = H.A$ with A as the area of cross section of the loop. The magnetization of this energy is given by,$M = \frac{\partial\in}{\partial H}$, so that

$$M = JA\sin\left[\frac{2\pi}{\phi_0}(\phi + LJ)\right]$$

So the susceptibility, $\chi = \frac{\partial M}{\partial H}$, so we get

$$\chi = \frac{2\pi A^2 J}{\phi_0}\cos\left[\frac{2\pi}{\phi_0}(\phi + LJ)\right]$$

This value of χ is negative (Meissner effect) only if the phase angle is $> \pi/2$ which is equivalent to saying that the Meissner effect is obtained for $H > H_0$ only, where

$$H_0 = \left(\frac{\phi_0}{4} - LJ\right)\frac{1}{A}$$

For magnetic field $H < H_0$, χ is positive (para-Meissner effect). Thus the para-Meissner effect is predicted from the phase factor. For small inductance of the current loop $L \approx 0$, so the phase term in the cosine function of the susceptibility expression becomes $\frac{2\pi\phi}{\phi_0}$. The cosine function changes its sign from positive to negative at an angle $\frac{\pi}{2}$. At this phase susceptibility also changes its sign from positive (para -Meissner) to negative (Meissner). At this point, $\frac{2\pi\phi}{\phi_0} = \frac{\pi}{2}$. This implies, $\phi = \frac{\phi_0}{4}$. Thus smallest observable flux becomes, $\frac{\phi_0}{4}$.

The magnetization of $Bi_2Sr_2CaCu_2O_8$ at low fields has been studied[5-6]. These works shows that at low fields magnetization is positive. It has been reported[9] that there are only certain size of the current-loops which give the para-Meissner effect. The phase difference between the the two electrons of a cooper pair causes a change in the sign of the magnetization leading to para-Meissner effect. Field cooled magnetization studied[10-11] for melt-textured $YBa_2Cu_3O_{7-\delta}$ samples and PME is observed in the low fields as well as little high fields. This was explained by strong flux pinning and inhomogeneous cooling of the sample.

CONCLUSION:

It is found that there is a limit of the magnetic field within which para-Meissner effect(PME) can be found.Thus the positive sign in the magnetization arises from the phase factor. The atomic paramagnetism arises from the unfilled d-shell of the transition elements. The pair current is diamagnetic for all the phases. Since there is no unpaired single electrons which give paramagnetism, so, it can be concluded that PME is not caused by atomic paramagnetism. The phase of the two electrons of the Cooper pair are so correlated that there is a change in the phase in going from the s-wave to the d-wave leading to positive (para-Meissner) magnetization. Minimum observable value of flux quantum $\frac{\phi_0}{4}$ also has been predicted.

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