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## Highlight of Würzburg-Bristol Collaboration

## Relativistic Approach to Dichroism in Superconductors

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The collaboration between the groups of Prof. B.L. Györffy, Bristol, UK, and Prof. E.K.U. Gross, Würzburg, FRG, focuses on applying the relativistic theory of superconductivity to study dichroism in superconductors.

A system is said to exhibit dichroism if the absorption of light depends on its polarization [1]. Usually dichroism occurs if time reversal symmetry is broken through external or internal ('exchange') magnetic fields. The former case corresponds to the Faraday or Kerr effect, depending on whether it is observed in transmission or reflection, while the latter case is referred to as spontaneous dichroism. Instead of broken time reversal symmetry, dichroism can also result from lack of inversion symmetry. In normal metals and ferromagnets these phenomena have been the subject of many theoretical and experimental investigations [1, 2]. For superconductors, on the other hand, very little is known about mechanisms and consequences of dichroism. The objective of the collaboration is to develop a systematic theory of dichroism in superconductors.

We use the Bogolubov-de Gennes (BdG) approach to inhomogeneous superconductors in magnetic fields [3], including relativistic effects [4], and employ perturbation theory to incorporate a variety of potential sources for dichroism. As a measure of dichroism we use the difference, $\Delta P = P_{LHP} - P_{RHP}$, in the power absorption of light with left-handed polarization (LHP) and right-handed polarization (RHP). $\Delta P$ is proportional to $\mathrm{Im}[\sigma_{xy}(\omega)]$, the imaginary part of the offdiagonal elements of the conductivity tensor [5] which govern all magneto-optical phenomena.

Recently the BdG equations were generalized to include relativistic effects on the single-particle level [4]. ¿From this generalization, the full form of the spin-orbit operator in superconductors is known to have offdiagonal elements involving the pair potential (anomalous spin-orbit coupling), in addition to the well-known diagonal spin-orbit terms which contain the lattice potential. We include the spin-orbit terms, as well as orbital currents and order parameter inhomogeneities via stationary perturbation theory.

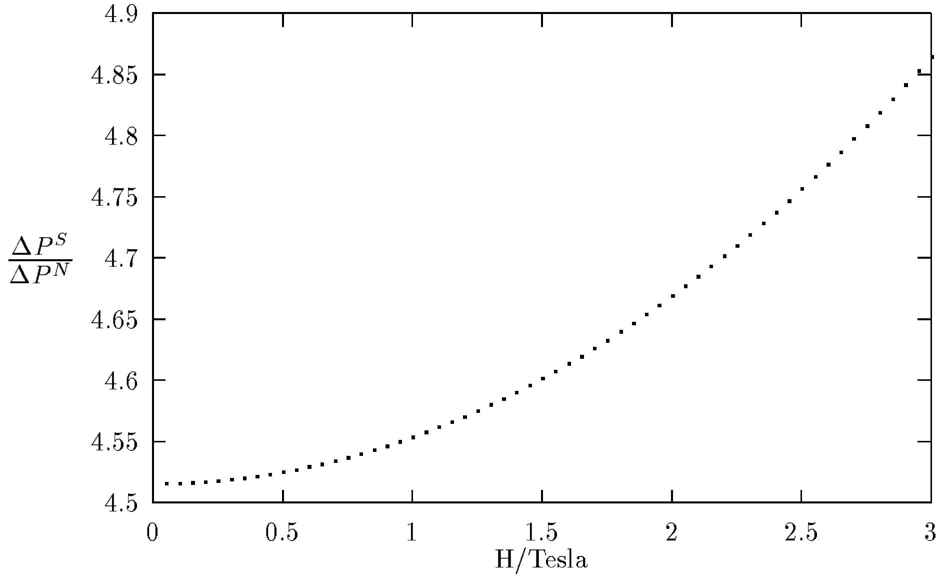


Figure 1: Dichroism ratio vs. magnetic field at $T = 3K$ for $\omega = 3meV$ and an energy gap at $T = 0$ of $2meV$.

Five distinct mechanisms which can give rise to a nonvanishing $\Delta P$ in superconductors were identified and interpreted in this way.

*Mechanism 1:* The conventional spin-orbit coupling (SOC) can, just as in normal metals, produce dichroism, provided that an (external or internal) magnetic field is present.

*Mechanism 2:* Anomalous spin-orbit coupling, too, can give rise to dichroism if magnetic fields are present. This term has a very different temperature behaviour compared to conventional SOC.

*Mechanism 3:* Orbital currents produced by $\mathbf{A}$, such as screening currents, can lead to a finite $\Delta P$, without SOC. In normal metals this is usually smaller than the effects due to SOC. In superconductors, where the screening currents responsible for the Meissner effect are particularly large, this need not be the case any more.

*Mechanism 4:* Even in the absence of magnetic fields and SOC, $\mathbf{r}$-dependent pair potentials are a possible source of dichroism if they are either complex (i.e. break time reversal symmetry), or break inversion-symmetry. This is particularly interesting because it makes dichroism a potential tool to investigate unconventional order parameters.

*Mechanism 5:* A material which lacks a center of inversion already displays dichroism in the normal state. Such a material in general also displays dichroism in the superconducting phase.

What all mechanisms have in common, is that time reversal symmetry or inversion symmetry is broken, by magnetic fields, by the pair potential or by the lattice potential. Mechanisms 1 and 3, which were investigated thoroughly for normal metals, are present in superconductors as well. However, we find that they are strongly modified by the superconducting coherence. This is illustrated by the figures to be discussed below. Mechanisms 2 and 4 are special to superconductors and not present at all in the normal state.

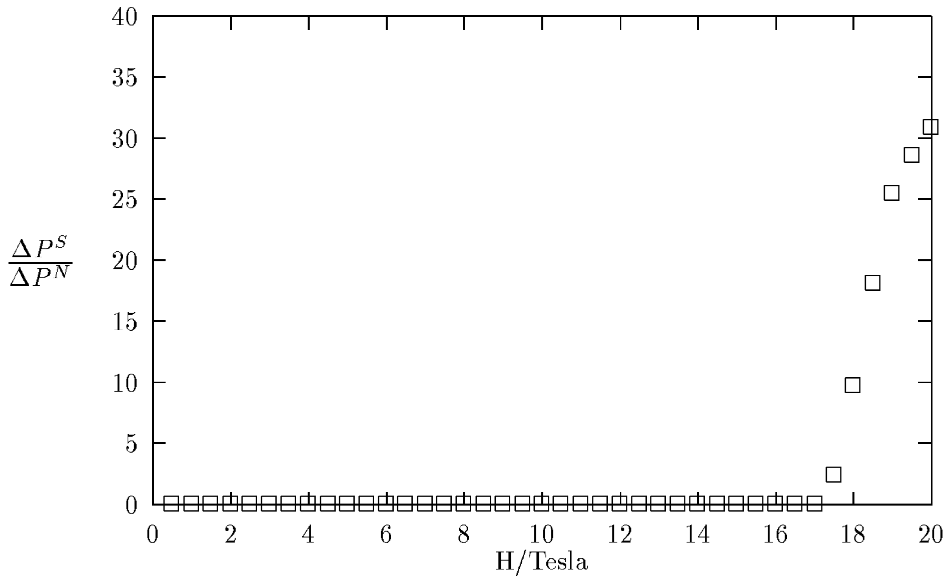


Figure 2: Same as in Fig. 1, but for $T = 0$ and fields up to the paramagnetic limit of superconductivity.

Those mechanisms requiring magnetic fields in the superconductor, namely 1, 2 and 3, cannot take place in the bulk of the material, as long as it is in the Meissner phase. They can be active in three different situations: (a) at surfaces, within the penetration depth, (b) in the vortex phase and (c) in superconductors displaying coexistence of magnetism and superconductivity. Mechanisms 1 and 2 are of relativistic origin. In particular, mechanism 2 constitutes the first potentially observable consequence of the anomalous spin-orbit coupling, predicted in [4].

Using simple approximations for the relevant matrix elements, we calculated $\Delta P$ for a model superconductor in which mechanism 1 is dominant. (Different model systems in which the other mechanisms dominate are currently under study.) In the plots we display the ratio of $\Delta P$ in the superconductor to $\Delta P$ in the normal conductor, $\Delta P^S/\Delta P^N$. This ratio is a direct measure for the interplay of relativistic symmetry breaking, due to mechanism 1, and superconducting coherence.

In Fig. 1 we plot $\Delta P^S/\Delta P^N$ versus the applied magnetic field. Both, numerator and denominator are almost linear functions of $B$ and vanish for $B = 0$. Their ratio, however, is an increasing function of $B$ because superconductors are more susceptible to magnetic fields than normal conductors. Repeating this calculation at $T = 0$, we find that the superconductor does not display dichroism for the fields in Fig. 1. This is physically reasonable, because at $T = 0$ a magnetic field will not produce spin polarization in a superconductor, since all electrons are paired. On the other hand it is known from normal state calculations that a finite spin magnetization is a necessary condition for SOC to produce dichroism. An alternative point of view is, that at $T = 0$ all paired electrons occupy mutually time conjugate states, so that the ground state is invariant under time reversal. Breaking this invariance, however, is mandatory for SOC induced dichroism.

In Fig. 2 we consider a superconductor with high upper critical field, $H_{c2}$. At zero temperature, we find, as before, $\Delta P^S \equiv 0$, until $B \approx 17.5T$. This is the field at which the Zeeman energy of

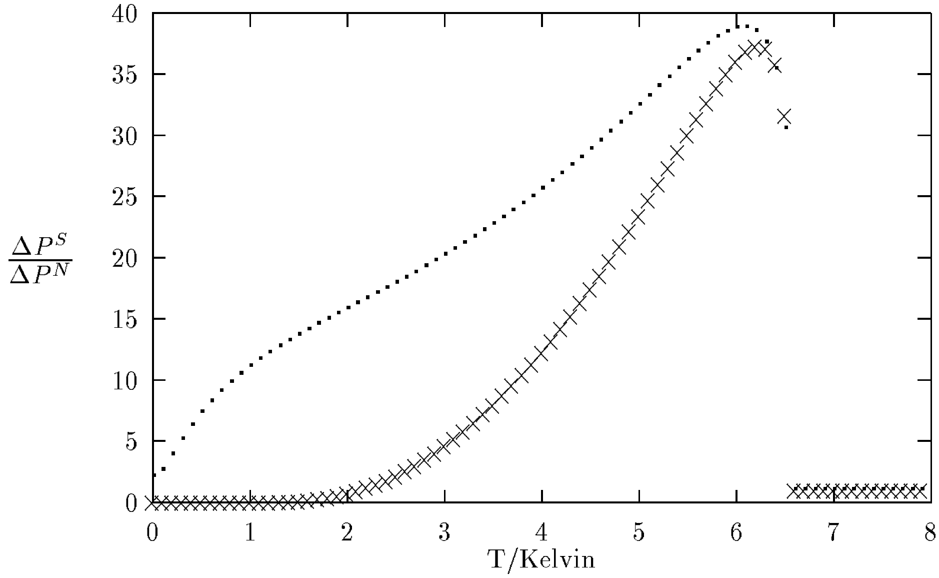


Figure 3: Dichroism ratio vs. temperature for $\omega = 4meV$ and $B = 0.1T$ (crosses) and $B = 17.5T$ (dots). $T_c$ is at $6.6K$. Hebel-Slichter- and gap-enhancement are seen.

the electron spins equals the energy gap. At this strength the magnetic field can break Cooper pairs paramagnetically. Once there are unpaired electrons, the magnetic field will immediately produce a net spin magnetization (hence break time reversal invariance) and dichroism results. Interestingly, this effect could lead to a very direct experimental identification of paramagnetic limiting as the cause of the upper critical field.

In Fig. 3 we keep the field fixed and vary the temperature. Above $T_c$ the ratio is unity. Right below $T_c$ we find a drastic increase in dichroism in the superconductor [6]. This increase can be partly traced back to a Hebel-Slichter like effect, due to a novel combination of coherence factors. A second amplifying mechanism is due to the presence of the superconducting gap, [9, 10].

The second graph in Fig. 3 is for $B > \Delta$, i.e. for the paramagnetic limit of superconductivity. The peak below $T_c$ is not affected much, but at $T = 0$ the curve for small fields goes to zero, while the curve for the paramagnetic limit approaches a finite value. This is in accordance with our discussion of Figs. 1 and 2.

In Fig. 4, finally, we display the frequency dependence of the absorption. There is an absorption edge at $\omega = 2meV$, which corresponds to the energy gap. This edge occurs because we considered only pair breaking processes [7]. The behaviour right above the edge is usually classified phenomenologically, according to the shape of the peak to be of type I or II [8], a classification which reflects the symmetry under time reversal of the perturbation (type I: odd, type II: even). The shape of the peak in Fig. 4 is of a mixed type, reflecting the fact that our model contains two perturbations, the polarized light (which is odd under time reversal) and the SOC (which is even).

The various plots demonstrate that even in the simple model many characteristics of the physics of dichroism and of superconductivity can be found. The exact numbers depend, of course, on the detailed parameters of the model. We believe, however, that the qualitative behaviour is generic, and constitutes a definite signature of the SOC mechanism.

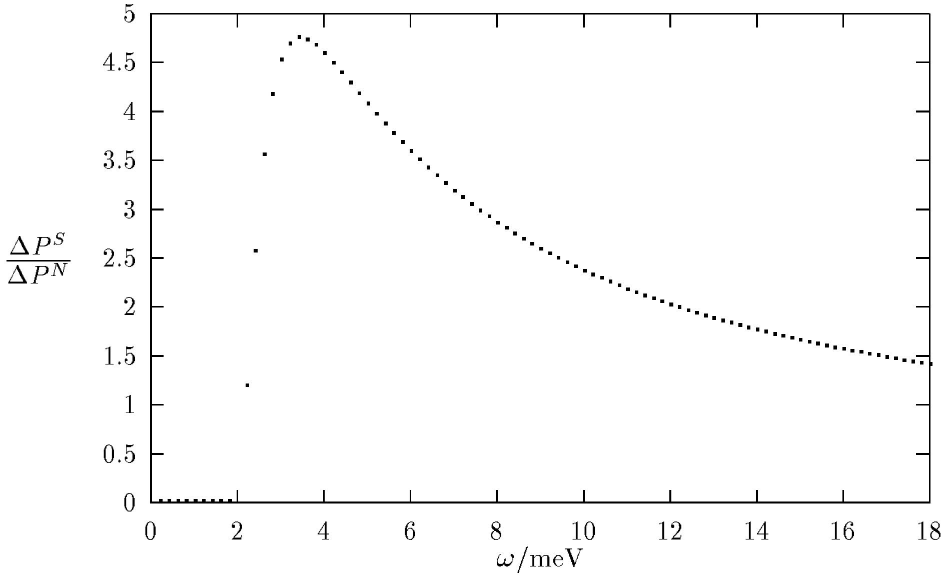


Figure 4: Dichroism ratio vs. frequency, at $T = 3K$ and for $B = 0.1T$. A mixed type I-II absorption edge at the gap energy of 2meV is present.

The above results have recently been submitted for publication [9]. A more detailed account of this work is currently being written [10].

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