CESR in superconductors: Relevance of high T_c copper oxide systems

S N EKBOTE

National Physical Laboratory, Dr K S Krishnan Marg, New Delhi 110012, India

Abstract. CESR is a highly effective tool to study the interaction among conduction electrons in normal metals. In superconductors below T_c it can reveal vital information concerning the pairing interactions. A comparative study of high T_c and conventional superconductors is presented and it is shown that the disappearance of CESR in the superconducting state is a feature common to both conventional and high T_c superconductors and establishes the importance of exchange interactions in pairing. This is supported by experimental observations.

Keywords. CESR; copper oxide system.

1. Introduction

The discovery of high T_c Cu-based oxide superconductors has not only given new imaginative horizons to experimental and the applied side of superconductivity, it has at the same time compelled theoreticians to look at the pairing and the mechanism of pairing in a totally new perspective. The realization of the importance of electron correlation in pairing (Anderson 1987), the passive role of mediating particles like phonons, plasmons, excitons, etc. and the positive role of magnetic state (Rice 1988; Schrieffer *et al* 1988) in the occurrence of superconductivity and so on, are some of the crucial parameters responsible for creating a stir in the conventional thinking for the origin of superconductivity. Within a span of two years many different theoretical approaches have been devised to understand the properties of new high T_c materials.

There have been numerous reports (Emery 1987, 1988) suggesting that in high T_c superconductors the magnetic state plays an important role in the formation of the superconducting state. The role of CuO plane (Wheatley *et al* 1988) and the d -band electron itinerancy has also been shown by the recent reports of NMR and spin-echo measurements (Alloul *et al* 1988). One expects a clear picture to emerge if the mechanism of pairing can be found unambiguously. Through CESR, the role of exchange interactions among conduction electrons has been established before for pairing in conventional superconductors (Ekbote *et al* 1980; Ekbote and Narlikar 1981a, b, 1982; Narlikar and Ekbote 1983; Ekbote 1988). (A good account of CESR in non-interacting and interacting systems can be found in the review by Platzmann and Wolff (1973)).

The CESR behaviour of conventional superconductors in their normal state above T_c (studied by our group for the elemental superconductors and Chevrel phases etc. of A-15 (Ekbote *et al* 1980; Ekbote and Narlikar 1981a, b, 1982; Narlikar and Ekbote 1983; Ekbote 1988)) shows that the Fermi liquid behaviour is very evident and the presence and dominance of exchange interactions is unavoidable; as the observed spin-wave resonance follows the Platzmann and Wolff behaviour and a dispersion relation given by

$$\omega_s = \omega_c \pm D^* k^2,$$

where w_c and w_s are resonant frequencies of CESR and spin waves respectively, $k = n\pi/L$; L being the thickness of the sample and D^* is the diffusion constant. Further, the vanishing of CESR near T_c and in the superconducting state suggests that the electron spins are coupled anti-parallel; above T_c , at T_c , and at $T_c/2$. This behaviour is most unexpected with conventional theoretical approaches. The absence of CESR just above T_c , and at T_c is an evidence of the electron spin correlation above T_c due to exchange interactions, as explained before (Narlikar and Ekbote 1983). The absence below T_c rules out the make-and-break process of BCS with relaxation time of 10^{-7} seconds because the frequency used for the CESR experiment is only 10^9 Hz. This makes the role of magnetic interactions among conduction electrons quite important in pair formation. A consolidated account of CESR and other studies like susceptibility, NMR, spin-echo etc. supporting the above contention in conventional superconductors has been published (Narlikar and Ekbote 1983).

2. Results and discussion

For this comparative study, the CESR behaviour of some conventional superconductors in normal, forced normal, and superconducting state is shown in figure 1a, and the CESR of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and Bi-Sr-Ca-Cu-O in normal and superconducting state is shown in figure 1b. Here, CESR of non-superconducting Y_{123} at 300 K and 80 K is also shown for comparison. These experiments on Y-Ba-Cu-O were carried out by two different groups. The first report on this system (Bhatt *et al* 1987) was brief in which only the observation of CESR and its disappearance in forced normal state (i.e. a state in which $T < T_c$ but the applied field is greater than H_{c2}) has been reported. The other experiment by Lue group (Lue 1988; Lue and Wu 1988) on $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and doped Y_{123} is much more elaborate, systematic and revealing. The researchers have shown the resolution of CESR, spin-waves at 300 K and the disappearance of CESR and spin waves at 80 K where the material is almost in the forced normal state (because of low critical field of Y_{123} at this temperature). Similar observations of ESR of the carriers related with superconducting state have been reported in Bi-Sr-Ca-Cu-O system (Hayashi *et al* 1989). CESR, as can be concluded from the shape and g -value (~ 2) of the signal, has been observed in normal state and disappears in the forced normal state at 108 K. The asymmetric shape also suggests the presence of spin wave resonance.

It is interesting to note that CESR of very simple metallic superconductors like Al (with a T_c of only 1.2 K), and of the highly complicated high T_c oxides like the Y_{123} system ($T_c = 90$ K) have shown many features which are common to both. In conventional superconductors, as shown in figure 1a, CESR is an unsymmetric absorption and the g -value is equal to nearly 2. The intensity and the linewidth do not change significantly with temperature and the CESR has spin-wave signals which move around the CESR with the orientation of disappearance of CESR in forced normal and superconducting state is a remarkable observation contradictory to theoretical predictions (Kaplan 1965; Maki 1973; Tagirov and Khushinov 1980). It is well known that the above properties in conventional superconductors above T_c are because of the conduction electrons exhibiting the single particle or fermion behaviour without any separation of charge and spin degree of freedom and forming a condensate. Similar observations in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, e.g. $g = 2$, presence of spin-waves and the disap-

Figure 1. The comparative conduction electron spin resonance of some of the conventional and high T_c superconductors in normal and superconducting states: **a.** Conduction electron spin resonance of some of the conventional superconductors showing PW (Platzmann and Wolff) type spin waves and the CESR. In the superconducting state the disappearance of all the resonances and in the forced normal ($T < T_c$ and $H > H_{c2}$) state the canting of electron spins are seen. **b.** Conduction electron spin resonance of some high T_c (Y- and Bi-based) materials showing similar behaviour as shown by conventional superconductors in figure 1(a). Note that in the case of nonsuperconducting YBaCuO sample the CESR does not vanish.

pearance of CESR etc. have been observed but the explanation given by Lue (1988) and Lue and Wu (1988) for spin-waves is based on an assumption that spin-waves result due to the coupling of conduction electrons and in low-lying states of the neighbouring spin due to the magnetic nature of lattices. This does not include the probability of Platzmann-Wolff (PW) spin-waves. This contention, however, does not look convincing as in normal metals and in conventional superconductors also these have been identified as the PW spin-waves by Dunifer *et al* (1977) in case of Al and in A-15's we have shown that the spin-waves are of PW type (Ekbote and Narlikar 1981). Another reason for calling them PW spin-waves is that in metals PW spin-waves are always close to CESR as observed in the case of Y_{123} and also that they do not need any internal field for their existence (as in Al, Nb_3Ge , $PbMo_6S_8$ etc. no internal field is expected). Interestingly, in non-superconducting Y_{123} neither the PW spin-waves are observed, nor the vanishing of CESR takes place which correlates these observations with the superconducting state. In the case of conventional superconductors, the disappearance of CESR has been reported earlier (Ekbote *et al* 1980; Ekbote and Narlikar 1981a, b, 1982; Narlikar and Ekbote 1983; Ekbote 1988), where it was also shown that closer the spin-waves to CESR higher is the T_c of the superconductor. Though the ESR of Bi-Sr-Ca-Cu-O system has not been studied so well, the presence of electrons and their participation in superconducting state through exchange interactions may be a possible inference in the light of the above discussion.

The above findings in the normal and superconducting state of Y_{123} , Bi-Sr-Ca-Cu-O and the conventional superconductors indicate the following features: First, the observation of CESR in normal state with $g = 2$ with low ΔH and ΔI variation with temperature strongly suggests the electronic nature of carriers as opposed to holes at the Fermi surface. The spin-wave resonance of Platzmann-Wolff type suggests confirmation of the correlation and exchange effects in conduction electron system. The vanishing of all signals shows the pairing of electron spins antiferromagnetically. In fact, our suggestion for conventional superconductors that the ground state is due to exchange interactions among conduction electrons also seems to be applicable to high T_c $YBa_2Cu_3O_{7-\delta}$.

References

- Alloul H, Mendels P, Collin G and Monod P 1988 *Phys. Rev. Lett.* **61** 746
 Anderson P W 1987 *Science* **235** 1196
 Bhatt S K, Ganguly P and Rao C N R 1987 *Pramana-J. Phys.* **L9**
 Dunifer G L, Pattison M R and Hsu T M 1977 *Phys. Rev.* **B15** 315
 Ekbote S N 1988 *Int. Conf. Cryo.* (abstract published, paper presented)
 Ekbote S N, Gupta S K and Narlikar A V 1980 *Solid State Commun.* **36** 117
 Ekbote S N and Narlikar A V 1981a *Solid State Commun.* **38** 1007
 Ekbote S N and Narlikar A V 1981b *IEEE Trans. Magn.* **MAG-17** 1664
 Ekbote S N and Narlikar A V 1982 in *Superconductivity in d- and f-band metals*, (Karlsruhe: KfK) p. 585
 Emery V J 1987 *Phys. Rev. Lett.* **58** 2794
 Emery V J 1988 *Nature (London)* **328**
 Kaplan J I 1965 *Phys. Lett.* **19** 266
 Hayashi Y, Sako S, Fukui M, Fujita T, Sasakura H, Minamigawa S and Nakahigashi 1989 *Jpn J. Appl. Phys.* **28** L1531
 Lue J T 1988 *Phys. Rev.* **B38** 4592
 Lue J T and Wu P T 1988 *Solid State Commun.* **66** 55
 Maki K 1973 *Phys. Rev.* **B8** 191

- Narlikar A V and Ekbote S N 1983 in *Superconductivity and superconducting materials*, (South Asian Publishers) p. 217
- Platzmann P M and Wolff P A 1973 in *Waves and interactions in solid state plasmas*, (Academic Press) Suppl. 13
- Rice T M 1988 in *Progress in high temperature superconductivity*, (World Scientific) Vol. 9 p. 15
- Schrieffer J R, Wen W G and Zhang S C 1988 *Physica* **C153–155** 21
- Tagirov L R and Khushinov M G 1980 *Sov. Phys. Solid State Phys.* **22** 328
- Wheatley J M, Hsu T C and Anderson P W 1988 *Nature (London)* **333** 121