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ORDER PARAMETER DYNAMICS AND COLLECTIVE MODES IN MAGNETIC IMPURITY DOPED SUPERCONDUCTOR

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Abstract. - Pair tunnelling has been used to probe the dynamics of the order parameter in the magnetic impurity doped superconductor Al(Er). The results have a bearing on the quantitative validity of the coupled system of equations for the dynamics of the order parameter and the non equilibrium quasiparticle distribution function.

Pair tunnelling in asymmetric junctions can be used to measure the imaginary part of the frequency and wave-vector dependent pair field susceptibility /1/ \( \chi''(\omega, k) \) of the lower \( T_c \) electrode of the junction near its transition temperature. \( \chi''(\omega, k) \) is proportional to an excess tunnelling current with \( \omega = \frac{2eV}{h} \) and \( k = \frac{2e}{\hbar} \sqrt{\frac{4}{2} + \frac{\lambda^2 \mathbf{H}}{2}} \).

Here \( V \) is the dc bias across the junction and \( \mathbf{H} \) is the magnetic field applied in its plane. \( \lambda \) is the London penetration depth of the higher \( T_c \) electrode of the junction and \( d \) is the thickness of the electrode whose susceptibility is being determined.

Below \( T_c \), the measured \( \chi''(\omega, k) \) changes dramatically from form found above \( T_c \). In place of the quasi-Lorentzian diffusive peak associated with fluctuations in the order parameter modulus, one finds a sharper peak at a voltage that increases with \( \omega = \frac{V}{(T-T_c)} \). A low frequency peak develops which is rather insensitive to \( \epsilon \). For large enough \( \epsilon \) an additional peak (or step) appears in the I-V characteristic at a voltage near the gap voltage.

The sharp peak has been identified with a propagating mode in the phase of the order parameter. It is believed to be a consequence of the coupling of the order parameter to fluctuations in the quasiparticle distribution function. This coupling term, known as the "anomalous term", converts the phase fluctuation equation into a damped wave equation. In terms of eigenfrequency solutions, the propagating mode frequency has a real (resonant) part which is greater than the imaginary (damping) part. In this regime, experiment and theory are only in qualitative agreement and further work is required /3/ to achieve a definitive test. The addition of magnetic impurities to the superconductor provides just such a test /4/. Impurities produce pair-breaking which depends on the spin-flip scattering time \( \tau_s \). This is an elastic scattering process which tends to suppress the anomalous term thus eventually resulting in an overdamping of the propagating mode.

In our experiments, we have used Pb-Al(Er) junctions with a thin layer of oxidized Al providing the tunnelling barrier. The edges of the films are masked with BiO3, leaving a junction area of \( (250 \mu \text{m})^2 \). The range of normal state resistances is from \( 0.05 \) to \( 0.5 \Omega \). There is a small linear leakage conductance which is usually \( 10^{-3} \) of the normal conductance. From the I-V characteristics above \( T_c \), where the theory is well understood, we can determine \( T_c \), the Pb gap, the diffusive constant \( D \) and the depairing parameter \( \rho \). The diffusion constant is obtained from the graph of the relaxation frequency vs. the square of the magnetic field, while \( \rho \) is determined from the graph of the relaxation frequency vs. temperature. \( T_c \) is determined by the onset of dc Josephson tunnelling.

In order to obtain the excess currents and \( \chi''(\omega, k) \) from the I-V characteristics, the single particle and leakage currents must be subtracted. The single particle current at fixed \( T \) and \( V \) depends only on the normal state resistance and the Pb gap. First the normal state resistance is meas-

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sured with both films in the normal state. Then
the Pb gap and leakage conductance are chosen so
that the resulting excess current fits exactly the
theoretical quasi-Lorentzian line shape. To meet
this criteria, we find the Pb gap is 1.36 mV at 1.2K
and is unique to about 1 μV! The leakage conductan-
ce is found to be a slowly varying linear function
of temperature having a small positive (sometimes
zero) TCR. Below Tc, parameters extrapolated from
T>Tc are used to obtain the excess current.

We have attempted a general analysis \( \chi''(\omega,k) \)
to obtain the parameters characterizing the dyna-
ics of the order parameter. This has involved a
multiparameter fit to a function consisting of the
sum of quasi-Lorentzians and shifted quasi-Lorent-
zians to account for the contributions to \( \chi''(\omega,k) \)
from the modulus and phase of the order parameter.
A smooth step function is used to account for the
feature near the aluminum gap. This analysis is in
qualitative agreement with the theories except in
the case of the longitudinal mode where the agree-
ment is quantitative. However, because the func-
tional forms employed are a gross over simplification
of those available theoretically, a comparison of
experiment and theory using exact functions is ne-
necessary. Such an analysis will be presented else-
where.

The dominant effect of increasing magnetic
impurities is to suppress the "anomalous term".
The existence of a non-zero depairing parameter
also leads to a gapless regime near \( T_c \) in which the
propagating mode is overdamped. The latter is the
major effect on the dynamics resulting from the
suppression of the "anomalous" term.

The value of the depairing parameter is deter-
mined from the reduction of the relaxation frequen-
cy in the normal state from its \( \rho=0 \) value. In
Figure 1 we plot \( \chi''(\omega,k) \) at fixed \( k \) for these films
with different depairing parameters. It should be
noted that the shape change usually associated with
the propagating mode, is absent in the gapless regi-
me. The widths of the gapless regimes as calculated
from \( \rho \) are consistent with those observed. When
superconductors with \( \rho \neq 0 \) are at sufficiently
low temperatures that they once again have a gap
and a propagating mode, the damping of the propa-
gating mode is greater than that observed in the
\( \rho = 0 \) case for a metal with the same value of \( k^2 \),
a result consistent with the predictions of theory.
It would be of interest to extend these investiga-
tions to fully-gapless superconductors where the
time-dependent Ginzburg-Landau equation should
apply in the superconducting as well as the normal
state.

![Fig. 1: Excess current-voltage characteristic](image)

**References**

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