The resonance observed in inelastic neutron scattering remains one of the most heavily debated features of cuprate superconductivity. Its initial observation in $Y\ B\ a_2C\ u_3O_{6+\delta}$ sparked numerous experimental and theoretical investigations. The detection of the resonance in $Y\ Sr\ a_2C\ u_3O_{6+\delta}$, together with several recent studies suggesting a direct link between the resonance and salient features of other experiments, give further support to the suspicion, that the neutron resonance is a key phenomenon in high $T_c$ superconductors.

Among the possible links, the one between the thermodynamic and magnetic anomalies deserves special attention. Taking a general argument by Scalapino and White further, Demler and Zhang pointed out that the emergence of a sharp resonance and superconducting long range order may be possible to check the link between the thermodynamic and magnetic measurements by starting from the specific heat dependence, and compared the outcome to the data of Loram and his collaborators. They concluded with the remarkable observation that the data are compatible with the prediction of a new property of the neutron resonance, that has not been observed yet. The aim of this paper is therefore to point out that (a) an upper bound can be given for $\Theta_{\text{res}}(T)$ in $Y\ B\ a_2C\ u_3O_{6+\delta}$, which in turn yields a reasonable account of $I_{\text{res}}(T)$; (b) the magnetic field sensitivity of $\Theta_{\text{res}}(T)$ constrains $I_{\text{res}}(T)$ to be strongly field dependent, and (c) an intimate connection exists between the presence of a sharp resonance and superconducting long range order. This last observation leads to a natural explanation of the predicted field-induced suppression in resonance intensity.

The procedure for obtaining an upper bound for $\Theta_{\text{res}}(T)$ is based on the observation that one can give a lower bound for the specific heat contribution $C_{\text{res}}(T)$ of single particle fermionic excitations. The fermionic specific heat contribution can be calculated from $\xi(T;\mathcal{V})$, corresponding to the fermionic part of thermodynamic potential.

$$\xi(T;\mathcal{V}) = \frac{1}{\mathcal{V}} \sum_{k_1} \ln \left[ \mathcal{G}_{k_1} \right]$$

where the single particle fermion propagator has the Nambu form $\mathcal{G}_{k_1} = \mathbf{1}_k$; $\mathbf{1}_k$ are Pauli matrices, and $\xi = \left( 2^N + 1 \right) k_b T$. Taking a general argument by Scalapino and White further, Demler and Zhang pointed out that the emergence of a sharp resonance and superconducting long range order. This last observation leads to a natural explanation of the predicted field-induced suppression in resonance intensity.

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neling measurements \cite{26}, and calculating the tunneling gap \cite{26} in the underdoped regime adds further support to the possibility that the gap is caused by the presence of bosonic excitation in the superconducting state. The expression in Eq. (4) will be used to separate from \(C_{el}\) the part that could, in principle, be due to bosonic excitations. This will be done by subtracting from \(C_{el}\) the fermionic contribution, computed from Eq. (4) and the thermodynamic relation \(C_\ell (T) = \frac{T^2}{\Theta^2} \cdot \epsilon (T; V) = \Theta^2 T^2\). There is no information available on the temperature dependence of \(\epsilon_k (T)\) in \(\text{YBa}_2\text{Cu}_3\text{O}_6+\_x\). Under these circumstances it is more useful to provide a controlled lower bound for the fermionic specific heat. This is possible to achieve by taking the low temperature gap value \(\Delta = 25\) meV from tunneling measurements \cite{16}, and calculating \(C_\ell (T)\) under the assumption that \(\epsilon (T; V)\) is constant at all temperatures. In this way one obtains a lower bound for the fermionic specific heat contribution, as compared to the case when \(\epsilon_k (T)\) is decreasing with increasing temperature. Clearly the constant gap model systematically underestimates \(C_\ell (T)\) in a system such as \(\text{YBa}_2\text{Cu}_3\text{O}_6+\_x\), where \(\Theta\) is close to \(T_c\). In the underdoped \(\text{YBa}_2\text{Cu}_3\text{O}_6+\_x\) samples, due to the onset of the pseudogap, the constant gap model becomes an even better approximation \cite{17}. Unfortunately, no tunneling data is available yet for such crystals.

Within the constant gap model Eq. (4) gives the following result for the fermionic specific heat

\[
C_\ell (T) = \frac{k_B}{2} \left( \frac{X}{k} \right) \text{sech}^3 \left( \frac{E_k}{2} \right) \cdot \frac{h}{k} \cdot \frac{1}{2} \left( \frac{E_k - \frac{2}{2} \text{cosh} \left( \frac{E_k}{2} \right)}{2} \right) + \frac{3}{2} \frac{2}{\text{E}_k} \cdot \frac{E_k}{2} \left( \frac{\text{E}_k}{2} \right) \left( \frac{\text{E}_k}{2} \right)
\]

(5)

The anomalous part, \(C_{res} (T)\), will be defined as the difference in the measured electronic specific heat \(C_{el} (T)\) and the fermionic contribution

\[
C_{res} (T) = C_{el} (T) - C_\ell (T).
\]

(6)

The specific heat data of Loram et al. for \(\text{YBa}_2\text{Cu}_3\text{O}_{6+\_y}\), displayed in the inset of Fig. 2 together with Eqs. (4) and (6), can now be used to compute the temperature dependence of the neutron resonance, as predicted by the thermodynamic data. At low temperatures this procedure gives

\[
C_{\ell}(T) = \begin{cases} 0 & \text{for } T < T_0 \\ C_{\ell}(T) = \theta^2 T^2 & \text{for } T > T_0 \end{cases}
\]

where \(\theta = \frac{\Delta}{\sqrt{2}}\), \(T_0 = \frac{\Delta}{2k_B}\), \(\Delta = 25\) meV, and \(\theta = 2.5\) K.

FIG. 1. Inset: The measured specific heat \(C_{el} (T)\) (dots), and the lower bound for the fermionic contribution \(C_\ell (T)\) (solid line), obtained by numerical evaluation of Eq. (5), using an s-wave gap \(\Delta = 25\) meV at all temperatures. The normal state density of states was fitted to reproduce the normal state data near \(T_0\). Main figure: The anomalous part, obtained by subtracting the calculated lower bound, \(C_{res} (T)\), from the experimental data, \(C_{el} (T)\). The effect of the magnetic field along the c-axis of the crystal is simulated by using the results of Ref. \cite{21}. The peak of the anomaly is gradually shifted to lower temperatures and reduced: 100% and 93 K (zero field, solid curve), to 71% and 89 K \((B = 1\) T, dotted curve), 45% and 81 K \((B = 3\) T, dashed curve), and finally 30% and 75 K \((B = 6\) T, dash-dotted curve).

While the deduced intensity is still the same order of magnitude as the experimental value of Ref. \cite{17}, the agreement is less striking. On the other hand, the fact that the resonance intensity required by the thermodynamic changes is smaller than that observed in neutron scattering supports the possibility that the source of superconducting condensation energy is in fact the gain in exchange energy, as suggested by Demler and Zhang \cite{19}. The deduced \(C_{res} (T)\) is somewhat affected by ambiguities in choosing \(T_0\), by experimental errors in the tunneling gap, and in the specific heat data itself, introduced by the necessary phonon subtraction. The normalized zero field intensity is shown as the solid curve in Fig. 2 together with the experimental data from Ref. \cite{17}. The agreement is satisfactory except near the transition temperature \(T_c = 92.5\) K, where the intensity is overestimated. This can be considered an indirect signature of superconducting gap dependence.

As pointed out by several groups \cite{22, 23}, the specific heat anomaly near \(T_c\) is removed in \(\text{YBa}_2\text{Cu}_3\text{O}_{6+\_y}\) by a magnetic field \(B = 10\) T along the c-axis, while \(C_{el} (T)\) away from \(T_c\) is unaffected. This is highly unusual, since the applied magnetic field is only a small fraction of the upper critical field \(B_{c2} = 100\) T. Similar effects have been recently documented...
in other cuprate materials as well [23,24]. The recent work of Junod and coworkers [24] presents an especially detailed account of the field dependence of the specific heat anomaly. They contrast the behavior seen in the cuprates with that in a low T_c superconductor (Nb-Zr alloy), where the anomaly is pushed to lower temperatures, but never removed. Indeed, the behavior seen in cuprates seems to go beyond the conventional framework, according to which as long as T_c is finite, the specific heat jump is also finite [25].

The most detailed set of data for the field dependence of the anomaly in YBa_2Cu_3O_6.93 was presented in Ref. [21]. In these measurements, however, the phonon background was not subtracted, as in the data Loram et al. used above. In order to avoid subtraction problems, the finite field specific heat jumps were obtained by imposing on Loram and coworkers’ zero field data [18] the suppression in the height and the shift towards lower temperatures of the specific heat maximum observed by Junod’s group [21]. The result is shown in the main part of Fig. 1.

When field-suppressed specific heat anomalies are used in Eq. (3), the resulting temperature dependence of the deduced resonance intensity deviates from what was measured in zero field, as shown in Fig. 2. In fact, these results show that \( T_{\text{res}}(B,T) \) should be depleted at low fields, and as the temperature is increased. Bourges et al. [29] measured the neutron resonance in a magnetic field and found \( T_{\text{res}}(6 K) \) to be sensitive to fields of order \( B \sim 12 T \) oriented along the ab-plane of the sample. Their result does not invalidate the claim of Dai et al., since in that geometry the specific heat anomaly is only moderately depressed, and not removed by the field [21]. However, the measurement of \( T_{\text{res}}(B,T) \) with \( B \) along the c-axis seems to be a crucial experiment for not only establishing the validity of Eqs. (1) and (2), but also to gain important insight into the nature of the neutron resonance itself.

The strong magnetic field dependence of the resonance predicted by the above procedure raises immediately a key question: What is the main mechanism responsible for inducing such a large change in the neutron intensity? In the remainder of this paper I will argue that there is an intimate connection between the resonance and correlations in the phase of the superconducting order parameter. This connection, besides offering a natural explanation for the field sensitivity of the resonance, also seems to have direct relevance to some puzzles in the nature of the neutron resonance itself.

The zero field properties of the resonance, like the existence of superconducting singularities significantly. Finally, a c-axis field strongly affects the specific heat jump and the resonance, but only mild changes are observed if the field is along the ab-plane [21], consistent with the results of Bourges et al. [29]. The strong dependence on the field direction suggests that Zeeman splitting is irrelevant and that the resonance is not affected by shielding currents along the c-axis itself, when the field is parallel to the CuO_2 planes. On the contrary, the resonance is affected considerably by the presence of in-plane shielding currents circulating around the cores of Abrikosov vortices, when the field is parallel to the c-axis. As discussed in more detail below, this translates to the statement that in-plane long range coherence as well as short range c-axis coherence (intra-bilayer) does matter for the resonance, whereas long range c-axis phase coherence does not.

In order to make these observations more transparent, it is instructive to examine the bare spin susceptibility, where the phase dependence is indicated explicitly [31].

\[
\begin{align*}
0(Q;i_n) &= \frac{1}{m} \sum_{p,m} G_G(Q;i_n) \\
&\quad + \frac{1}{f} \sum_{p,m} F_F(Q,\{i,m\}) \langle \Phi(\{1,m\}) \rangle \tag{7}
\end{align*}
\]

Here \( G_G(Q;i_n) \) and \( F_F(Q;i_n) \) are the normal and superconducting contributions to the bare susceptibility, \( F_F(Q;i_n) = \frac{1}{m} \sum_{k} \{ F_k + \epsilon_q \} F_k(\cdot) \), and \( \epsilon_q = 2m \kappa_q T \). A similar expression holds for \( G_G(Q;i_n) \), but with the Gor'kov propagators replaced by the diagonal part of the superconducting Green’s function. The function \( \Phi(\{1,m\}) \) is the Fourier and Matsubara transform of the charge displacement correlation function \( \langle \Phi(\{1,m\}) \rangle \) (x & y; \( \phi = \frac{\pi}{2} ; \), z; \( \theta = \frac{\pi}{2} ; \)), and \( \phi = \frac{\pi}{2} \) is the phase of the superconducting order parameter at position \( x \) and imaginary time .

Equation (7) can provide new insights even for the zero field case. In the absence of phase fluctuations, corresponding to
In general, a form of scopic and thermodynamic properties of cuprate superconductors, Raman scattering cross section, and other spectroscopic field behavior of optical conductivity, tunneling density of states. A detailed study of all these effects is currently under the U.S. DOE, BES, under Contract No. W-31-109-ENG-38.

The weak interplane coupling and strong two dimensionality, quantum phase fluctuations can be quite large, and consequently very small. In contrast to single layer materials, the strong Josephson coupling between bilayers can stabilize the superconducting state with a rigid phase. This could be the main reason why the neutron resonance has only been observed in bilayer materials, and not in single layer materials, such as La$_2$Sr$_2$CuO$_4$. The broad maximum observed in the pseudogap regime of underdoped Y Ba$_2$Cu$_3$O$_{6+x}$ could be the precursor of the resonance below $T_c$, provided that strong pairing fluctuations are present in this regime.

In the Abrikosov vortex phase induced by a field along the c-axis, the weight of $\langle \psi^2 \rangle$ is no longer concentrated at long wave lengths and low frequencies. As shown by Glazman and Koshelev, the vortex lattice destroys the off-diagonal long range order in the planes at finite T, while long range order along the field direction is broken only at elevated temperatures. For the in plane correlations, they find $\ln r: l (q; z = 0) = \ln r: l \exp \{ \pm \phi \}$, where $\phi = \frac{\theta}{B}$ is the in-plane phase correlation length in magnetic field. Thus, the field will induce a momentum broadening $\frac{\hbar}{B}$ in the resonance, and a reduced intensity.

The arguments presented above are quite general and consequently have direct relevance not only to the magnetic field dependence of the neutron resonance, but also to the finite field behavior of optical conductivity, tunneling density of states, Raman scattering cross section, and other spectroscopic and thermodynamic properties of cuprate superconductors. A detailed study of all these effects is currently under way, and will be reported in a later publication.

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