The Neutron Spin Resonance in Superconductors
Is It Really a Spin Triplet?

Mike Norman

Materials Science Division
Argonne National Laboratory
&
Center for Emergent Superconductivity

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Phase Diagram of the Cuprates

Temperature (Kelvin)

Hole Doping (x)

Antiferromagnet

pseudogap

"normal" state

T_N

T*

???

T_c

T_coh (?)

Fermi Liquid

superconductor

spin glass

0 0.05 0.1 0.15 0.2 0.25 0.3
d-wave pairing observed by phase sensitive tunneling
(van Harlingen, Kirtley & Tsuei)

Superconducting Energy Gap from Photoemission
Shen et al, PRL (1993); Ding et al, PRB (1996)

\[ \Delta_k \propto \cos(k_x a) - \cos(k_y a); \quad \Delta_k = -\Delta_{k+Q} \text{ where } Q=(\pi,\pi) \]
Neutron Spin Resonance below $T_c$ (triplet excitation?)
Rossat-Mignod, Bourges, Mook, Dai, Keimer, ...

YBa$_2$Cu$_3$O$_{6.6}$ ($T_c = 62.7$ K)

Dispersion of magnetic excitations has the form of an hourglass ("d-wave RPA" or "stripes & ladders")

Arai et al., PRL (1999)
The hourglass has a twist
(2D pattern rotates by 45 degrees from below resonance to above)
Phase Diagram of Iron Arsenide Superconductors

Drew et al., Nat. Matls (2009)

Canfield & Bud’ko, ARCMP (2010)
Energy Gaps from ARPES (K-doped 122)

Ding et al., EPL (2008)
Quantum Interference in FT-STM (FeSe-Te)

Hanaguri et al., Science (2010)
Spin Resonance Mode in Superconducting Phase
(K-doped 122)

\[ \Delta_k = -\Delta_{k+Q} \]

Christianson et al., Nature (2008)
Scaling of Resonance Energy with $T_c$ (as previously observed in the cuprates)

CeMIn$_5$ - LANL group – PRL 2000, EPL 2001, JPCM 2001

Pfleiderer, RMP (2009)
Magnetic Resonance in CeCoIn$_5$

Stock et al., PRL (2008)
RPA Theory

\[ \chi^{\text{irr}} = \left\langle \begin{array}{c} \bullet \\
\end{array} \right| \left. \begin{array}{c} \bullet \\
\end{array} \right\rangle + \left\langle \begin{array}{c} \bullet \\
\end{array} \right| \left. \begin{array}{c} \bullet \\
\end{array} \right\rangle \]

\[ \chi_0(q, \omega) = \sum_k \left\{ \frac{1}{2} \left( 1 + \frac{\epsilon_k \epsilon_{k+q} + \Delta_k \Delta_{k+q}}{E_k E_{k+q}} \right) \frac{f(E_{k+q}) - f(E_k)}{\omega - (E_{k+q} - E_k) + i\delta} \right. \\
\left. + \frac{1}{4} \left( 1 - \frac{\epsilon_k \epsilon_{k+q} + \Delta_k \Delta_{k+q}}{E_k E_{k+q}} \right) \frac{1 - f(E_{k+q}) - f(E_k)}{\omega + (E_{k+q} + E_k) + i\delta} \right. \\
\left. + \frac{1}{4} \left( 1 - \frac{\epsilon_k \epsilon_{k+q} + \Delta_k \Delta_{k+q}}{E_k E_{k+q}} \right) \frac{f(E_{k+q}) + f(E_k) - 1}{\omega - (E_{k+q} + E_k) + i\delta} \right\}, \]

\[ \chi(q, \omega) = \frac{\chi_0(q, \omega)}{1 - U \chi_0(q, \omega)} \]
In d-wave case, Im $\chi_0$ has a step, Re $\chi_0$ is log divergent, at $\omega=2\Delta$. 

\[ \text{Re} \chi_0(\omega) \sim \frac{\nu_F \Delta_{hs}}{E_F} \ln\left[ \frac{\Delta_{hs}}{(\omega_{t\sigma} - \omega)} \right] \]

\[ \text{Im} \chi_0(\omega) \]

\[ \frac{\nu_F \Delta_{hs}}{E_F} \quad 1/U_q \]

$\omega_{res}$, $\omega_{t\sigma} = 2\Delta_{hs} - 2\sigma \mu B$
2D Fermi Surface Nesting Explanation of Incommensurability

2D Fermi surface for Bi2212

2D Fermi surface translated by $Q=(1+\delta,1)$
($\pi/a$ units)

Schultz - PRL 1989
Brinkmann & Lee - PRL 1999
Norman - PRB 2000, 2001
Linear response (RPA) calculations of the spin dispersion can account for the hourglass and its twist through the resonance.

These calculations assume a 2D Fermi surface plus d-wave pairs (Norman - PRB 2000, 2001, 2007).

See also Eremin et al, PRL (2005)
Spin resonance for $s_\pm$ state

Korshunov & Eremin
PRB (2008)

Maier & Scalapino
PRB (2008)
In the isotropic case, the resonance should be a triplet which will split in a magnetic field.
But no detectable splitting was observed in YBCO.
Polarized neutrons, though, indicate an isotropic response at resonance (consistent with a triplet)
Is it a Triplet (FeSe-Te)?

Bao et al., arXiv:1002.1617

Babkevich et al., PRB (2011)
Is it a Doublet (FeAs-122)?

Ni-doped Ba122

Lipscombe et al., PRB (2010)
But no splitting is observed

Ni-doped Ba122

Li et al., PRB (2011)
Role of Anisotropy

\[ S_+ (Q) |S=0, q=0> = |S=1, S_z=1, q=Q> \]
\[ S_- (Q) |S=0, q=0> = |S=1, S_z=-1, q=Q> \]
\[ S_z (Q) |S=0, q=0> = |S=1, S_z=0, q=Q> \]
AF superconductor – SC order parameter is a mixture of a spin singlet ($Q=0$) and one component of a spin triplet ($Q=Q_{AF}$)
Hourglass in a cobalt oxide ($\text{LaSrCoO}_2$)

Boothroyd et al., Nature (2011)
Antiferromagnetic spin fluctuations can lead to pairing (an e\textsuperscript{-} with up spin wants its neighbors to have down spins)

Heavy Fermions - Varma (1986), Scalapino (1986)
High T\textsubscript{c} - Scalapino (1987), Pines (1991)
What is the origin of pairing?

Is there a pairing glue?

Is it instantaneous?

“We have a mammoth and an elephant in our refrigerator—do we care much if there is also a mouse?”

Pairing strength versus frequency

\[ I(k_A, \Omega) = \frac{2}{\pi} \int_0^\infty \frac{\phi_2(k_A, \omega)}{\omega} d\omega' \]

\[ \chi''(\Omega) = \text{U}=10 \]

Maier, Poilblanc, & Scalapino, PRL (2008)