H2. SPIN-GAP CLOSING UNDER MAGNETIC FIELD IN THE ELECTRON-DOPED HIGH-TC SUPERCONDUCTOR: $Nd_{1.85}Ce_{0.15}CuO_4$

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Understanding the nature of superconductivity in high-T_c superconductors requires the characterization of the various phases (antiferromagnetic insulating, spin-density wave, charge-density wave…) that may compete with the superconducting state.

Up to now, this has been achieved mainly by studying the properties of these compounds upon varying external parameters such as the carrier concentration or the temperature. However, the effect of a strong magnetic field has been much less studied. As a consequence, the nature of the field-induced ground state is still an open question.

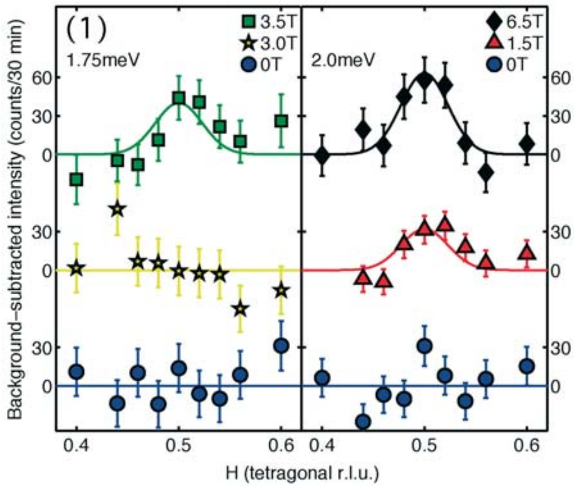

Figure 1. Transverse scans (h 1-h 0) through the AF zone center (1/2, 1/2, 0) at an energy transfer of ε = 1.75 meV (left) and ε = 2.0 meV (right). Before each scan, the sample was field-cooled from above T_c to T = 1.8 K. Typical counting time is 30 min. per point.

In this study, we use inelastic neutron scattering to determine the magnetic-field effect on the superconducting spin-gap of $Nd_{2-x}Ce_xCuO_4$, the prototype of electron-doped high-T_c superconductors. A detailed report of the results was published in Ref. [1]. The dynamic susceptibility $\chi''(\boldsymbol{q}_0,\varepsilon)$ near the antiferromagnetic (AF) point $\boldsymbol{q}_0$ = (1/2, 1/2, 0) has been measured as a function of energy for different magnetic fields using the same method as used in our previous zero-field study [2].

In Fig.1, showing a typical q scan at constant energy for different fields, one sees how an applied magnetic field can cause the signal, which was initially suppressed by the spin-gap opening, to reappear. Before each scan, the sample was first heated above T_c and then cooled down in the new field back to T = 1.8 K; this procedure was followed in order to ensure a macroscopically uniform internal field. At an energy transfer of ε = 1.75 meV [Fig. 1(a)], the magnetic excitations are completely suppressed up to H = 3 T, and reappear at 3.5 T. A similar behavior is seen at the slightly higher energy transfer of ε = 2.0 meV [Fig. 1(b)]. In this case, the peak is seen to reappear at a lower field of H = 1.5 T

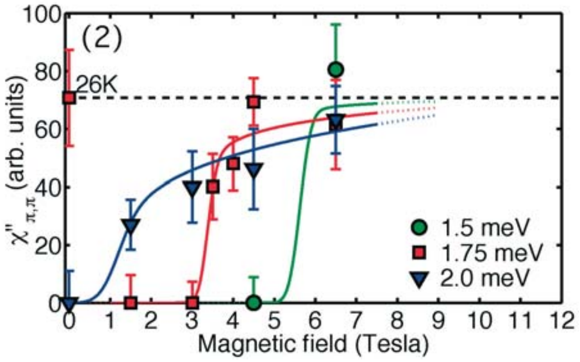

Figure 2. Dynamic susceptibility $\chi''(\boldsymbol{q}_0,\varepsilon)$ at $\boldsymbol{q}_0$ = (1/2, 1/2, 0) as a function of field at several energies. All data are taken at T = 1.8 K except the zero-field point at T = 26 K.

Figs. 2 to 4 summarize the experimental results obtained on the triple-axis spectrometer 4F2 at LLB.

For hole-doped materials, the upper critical field at which superconductivity is completely destroyed is ~50 T or larger [3], prohibitively large for neutron scattering experiments. For the electron-doped materials, on the other hand, H_{c2} is relatively lower (~10 T) [3], which has allowed us to observe a field effect on the superconducting magnetic gap in $Nd_{2-x}Ce_xCuO_4$ up to high values of the relative magnetic-field strength.

Fig. 2 shows the evolution of the magnetic signal with magnetic field for energies within the zero field gap. The signal remains zero up to a threshold field which depends on energy. Then the signal increases with field, which is a first indication that the gap decreases. The horizontal dashed line represents the signal measured above T_c (T = 26 K) showing that the dynamical susceptibility at high H and low T is essentially the same as above T_c in zero field.

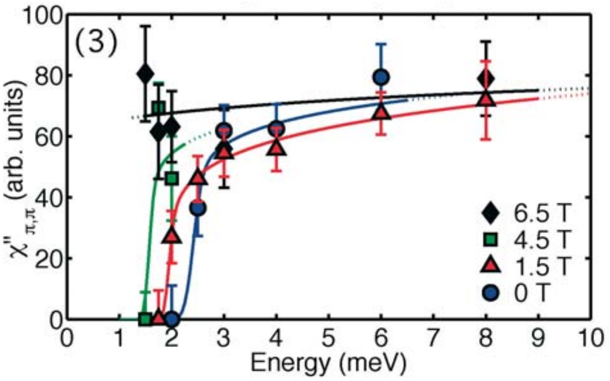

Figure 3. Field dependence of the magnetic excitation spectrum $\chi''(\boldsymbol{q}_0,\varepsilon)$ as a function of energy at T = 1.8 K. Curves are guides to the eye.

Fig. 3 shows the dynamical susceptibility $\chi''(\boldsymbol{q}_0,\varepsilon)$ for several fields up to 6.5 T. The zero-field gap energy in our sample is 2.5 meV, slightly smaller than in a previous work [2], in accordance with our somewhat lower T_c. It decreases down to 1.5 meV at 5 T. At H = 6.5 T, we have not been able to measure the gap because of the dominating magnetic excitations of Nd at low energies. These results can be interpreted as a rigid down shift of the gap profile with field.

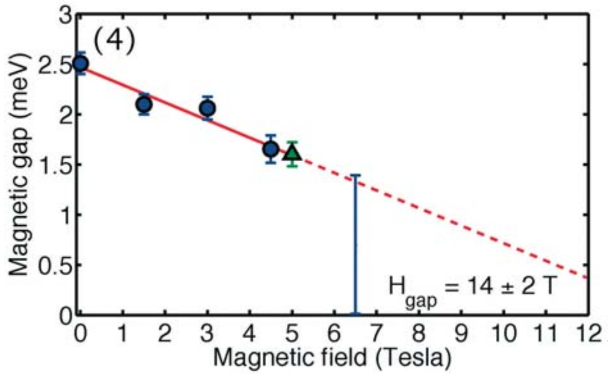

Figure 4. Evolution of the magnetic gap (half-maximum energy) as a function of field. The dependence is linear and extrapolates to zero at H_{gap} ~14.2 T. The vertical bar reflects the fact that the gap energy is less than 1.5 meV.

Our results do not show any field-induced excitation in the gap as reported for the $La_{2-x}Sr_xCuO_4$ compound [4-6].

In Fig. 4, the gap energy is plotted as a function of field. The magnetic gap decreases linearly with field, and collapses completely at an extrapolated value of H_{gap} ~14.2 T, consistent with an upper critical field of H_{c2} ~10–12 T [3]. The gapped spectrum of $Nd_{2-x}Ce_xCuO4$ undergoes a rigid shift towards lower energies as the magnetic field is increased, which is in strong contrast to the formation of in-gap states in optimally doped and slightly overdoped $La_{2-x}Sr_xCuO_4$ [4-6]. Because measurements below 1.5 meV were not possible, it is natural to ask whether the formation of some in-gap states in $Nd_{2-x}Ce_xCuO_4$ could be hidden below this energy. However, we emphasize that the signal strength at 1.5 meV remains zero up to 4.5 T. Since our energy resolution is 1.3 meV (full width at half maximum), the experiment is sensitive to any in-gap intensity down to very low energies.

The results point to a picture in which the non-superconducting ground state at fields above H_{c2} does not possess magnetic order, but is a paramagnet with AF fluctuations. The first piece of evidence is that, in $Nd_{1:85}Ce_{0:15}CuO_4$, applying a magnetic field and increasing temperature have similar effects, and the gap does not appear to close until superconductivity is completely suppressed [7]. Moreover, the signal strength seen at high magnetic fields equals that in the normal state just above T_c. All of this indicates that the non-superconducting ground state beyond H_{c2} resembles the paramagnetic normal state above T_c.

The absence of magnetic-field-induced in-gap states in $Nd_{1:85}Ce_{0:15}CuO_4$ and the likely absence of field-induced magnetic order imply an important difference between the electron-doped and hole-doped cuprates; the competing spin- (and charge-) density wave order (often referred to as “stripes”) observed in hole-doped superconductors, especially in materials derived from the high-T_c parent compound La_2CuO_4, hinders an unobstructed study of the AF-correlated superconductor due to the presence of a nearby quantum critical point. This complication appears to be avoided by the electron-doped materials, which possess the additional experimental advantage of a relatively low upper critical field.

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