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# Recent neutron-scattering results on high-temperature superconductors

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**Abstract**

Triple-axis spectrometry has been used to determine the magnetic excitations in $YBa_2Cu_3O_7$. Polarized measurements at 10 K show the scattering consists of a peak near 40 meV while 100 K data show a mostly flat continuum. At 10 K the 40-meV peak is found to be sharp in energy and anisotropic in momentum occupying a square portion of the Cu–O reciprocal lattice plane. The temperature dependence of the scattering is identical at the square side and corner. Polarized measurements show that the small background scattering observed at 100 K disappears below the superconducting transition. Resonant absorption measurements made to examine the Cu phonons show no observable changes in the phonons at the superconducting transition.

There has been a large number of neutron studies on high-temperature superconductors that have yielded very important results concerning several aspects of the high-$T_c$ problem. These would be difficult to cover even in a lengthy manuscript, so we limit ourselves to recent neutron-scattering measurements on $YBa_2Cu_3O_7$ (Y123). Most of the measurements concern the magnetic fluctuations for the material; however, some measurements on the lattice dynamics will be mentioned at the end of the article.

The measurements on the magnetic excitations have been performed on large crystals of Y123 that range from 8 to 15 g in weight and have mosaic spreads on the order of 1.5°. Most of the measurements were made on two crystals mounted together giving a combined weight of about 20 g. The crystals contain a considerable amount (15%) of $Y_2BaCuO_5$ as an impurity. This material is found in large pores of the crystals and is oriented randomly with respect to the crystal lattice. We have studied the temperature dependence of the scattering of a large powder sample of $Y_2BaCuO_5$ to make sure that none of the effects which we ascribe to Y123 actually occur in the impurity phase. The crystals contain no other phases of significance. It is difficult to ascertain the exact oxygen concentration of such large crystals, but bulk measurements on similar smaller crystals result in oxygen concentrations very near $O_7$. Lattice-constant measurements for the crystals confirm that the entire sample has an oxygen concentration consistent with the $O_7$ value. The

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crystals show superconducting transitions at 92.4 K that are 1 K wide. Measurements of the vortex lattice have been made with the crystals used in the experiment, and the intensity of the scattering from the vortex lattice [1] shows that the entire crystal exhibits bulk superconductivity.

Fig. 1 shows the reciprocal lattice of Y123 for the $a^*$, $b^*$ directions, shown in square lattice notation. Our crystals are all highly twinned so that we cannot distinguish $a^*$ from $b^*$ in our measurements. We find the magnetic response to center on $\pi$, $\pi$ and we have performed numerous scans in the direction (0, 0 to $2\pi$, $2\pi$) which we will denote as ($\pi$, $\pi$) scans and along the direction (0, $\pi$ to $2\pi$, $\pi$) which we will denote as (0, $\pi$) scans.

We have found the phonon scattering in the sample to be much larger than the magnetic scattering in some cases. This means that when a scattering signal is found, polarization analysis must be used to confirm that the scattering is magnetic in nature. If the unpolarized scan results in no signal being observed, it can be relied on to prove that no excitation of any type exists in the region being probed or that the scattering is small and featureless and thus difficult to distinguish from the background. For polarized scans it is often sufficient to measure the spin-flip scattering (SF) and the non-spin-flip scattering (NSF). The SF will give the background plus magnetic scattering, while the NSF will give the background plus nonmagnetic scattering. Generally the background can be established to be quite flat so that a peak in the SF scattering, corrected for any imperfect-polarization effects, can be assumed to be magnetic. In questionable cases or where the scattering is flat, the SF scattering can be measured with the neutron polarization first parallel to the neutron momentum transfer (HF) and then perpendicular (VF). The difference HF–VF will then give half the magnetic intensity, completely free of background effects [2]. This type of measurement is very reliable since only the field changes direction, and all background effects cancel. Polarized measurements result in a loss in intensity of a factor between five and ten, and the HF–VF case is yet more difficult, as two measurements are needed resulting in half the intensity.

At low temperatures we find the dominant feature in the magnetic scattering to be a peak near 40 meV as observed in earlier measurements [3]. Fig. 2 shows a ($\pi$, $\pi$) polarized, (HF–VF), scan taken at 100 K. All our scans shown were taken with a $c$-axis component on the peak of the bilayer structure factor [4], so that the scattering can be thought of as stemming from acoustic magnetic excitations. Since we have done a (HF–VF) measurement the only scattering observed is magnetic. The 100 K scattering is found to be weak and quite featureless except for a possible remnant of the 40 meV peak. Further measurements are now in progress to see if the 40 meV peak actually remains in the normal state. Earlier measurements have shown that the intensity at 40 meV narrows in momentum $q$ as the temperature is lowered and the peak height grows correspondingly.

Previous polarized measurements [3] have shown that the phonons do not change much between 100 and 10 K so that we can examine the 40 meV scattering with unpolarized neutrons if we employ temperature differences. Fig. 3(a) shows a (0, $\pi$) result through the peak obtained

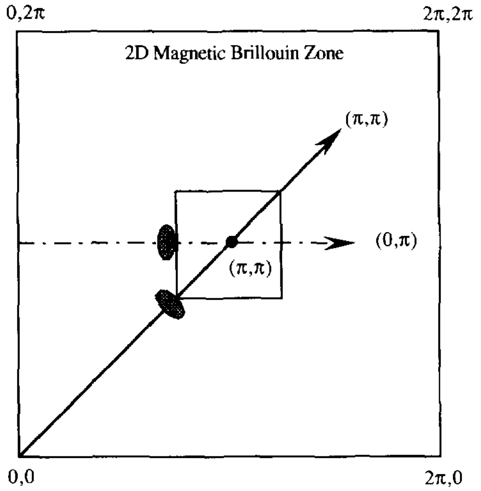


Fig. 1. Diagram of the 2-D magnetic Brillouin zone in square-lattice notation. The smaller square gives the half-width of the scattering found at about 40 meV, and the ellipses show the resolution used in the measurement.

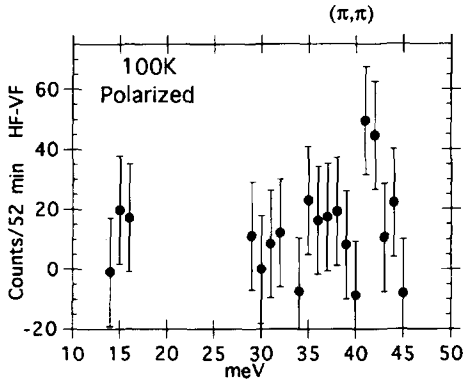


Fig. 2. Polarized-beam determination of the energy dependence of the magnetic scattering at ($\pi$, $\pi$). The measurements were made by the HF–VF technique which isolates only the magnetic scattering. There is a region centered around 25 meV where large parasitic scattering from the (0, 0, 6) reflection makes measurements impossible with the crystal orientation used.

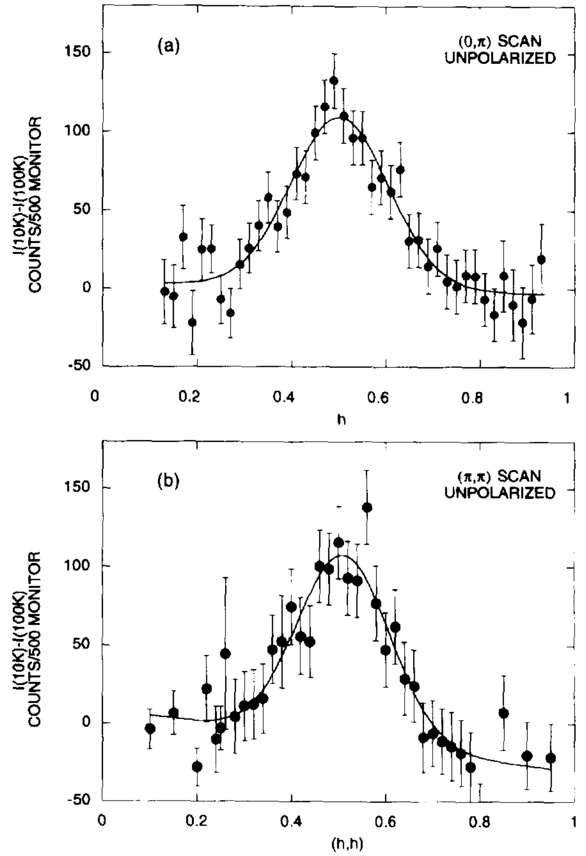


Fig. 3. (0, π) scans and (π, π) scans through the feature found near 40 meV. The data represent the difference between a measurement taken at 10 K and one taken at 100 K.

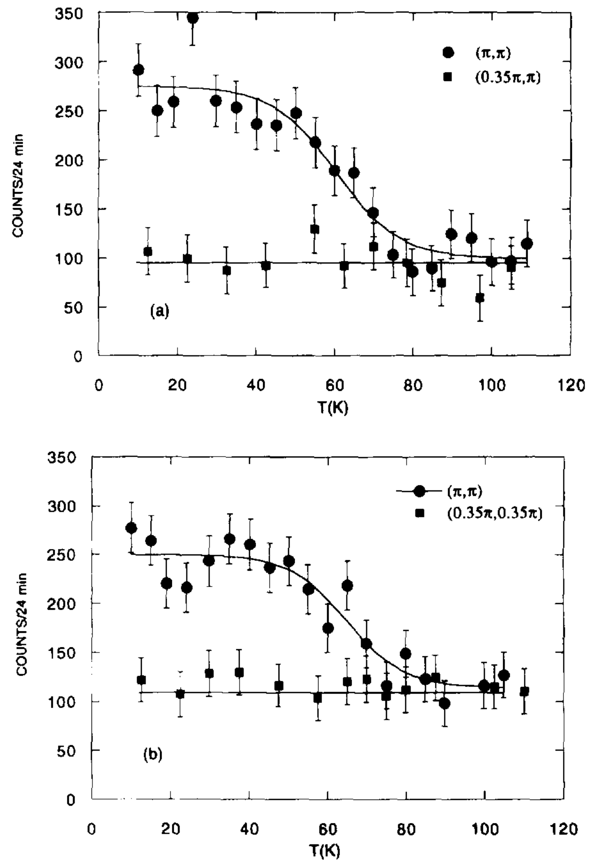


Fig. 4. Temperature dependence of the scattering from the 40-meV feature. Measurements were taken in crystal orientations to sample the scattering at the reciprocal lattice square corner and edge. The circles give the scattering at (π, π) for the two orientations while the squares give the intensity slightly outside the half-width of the 10-K distributions. Background scattering found at the zone boundary has been subtracted from the data.

by subtracting the 100-K data from 10-K data. We see the peak is about 0.24 momentum units wide along the scan direction, while Fig. 3(b) shows the result for a (π, π) scan in which the peak is essentially the same width in units of the scan, or $\sqrt{2}$ wider in momentum units. The actual peak width must be obtained from a deconvolution of the data from the spectrometer resolution. The scan directions and the size and position of the resolution ellipses are shown in Fig. 1. The resolution-corrected widths are 0.35 $\text{Å}^{-1}$ for the (0, π) scan and 0.49 $\text{Å}^{-1}$ for the (π, π) scan. The 40-meV feature is thus not circular around (π, π) as would be expected for a conventional spin-wave excitation with a dispersion governed by a simple exchange interaction. The feature instead appears to have the square symmetry of the reciprocal lattice and thus be associated with the Fermi surface. The size of the area covered by the 40-meV feature relative to the square zone is shown as the smaller square in Fig. 1.

Since the scattering appears to result from a Fermi-surface effect, it is interesting to examine the temperature dependence of the 40-meV feature and to see if there is any difference in its behavior at the half-width position at the square corner in the (π, π) direction from the half-width position at the square edge in the (0, π) direction, as might occur from anisotropic superconducting pairing. Figs. 4(a) and (b) show the result for the two directions. The data shown have a background scattering subtracted from it as determined by a measurement at the zone boundary on the low-$q$ side of the scans shown in Fig. 3. This is not the entire background as the background increases with $q$. The temperature dependence of the feature measured at (π, π) given by the open circles must be the same in both measurements and agree with the earlier measurement [3]. This is in fact the case. The points denoted by the squares are taken slightly outside the half-widths of the scattering distributions at 10 K for

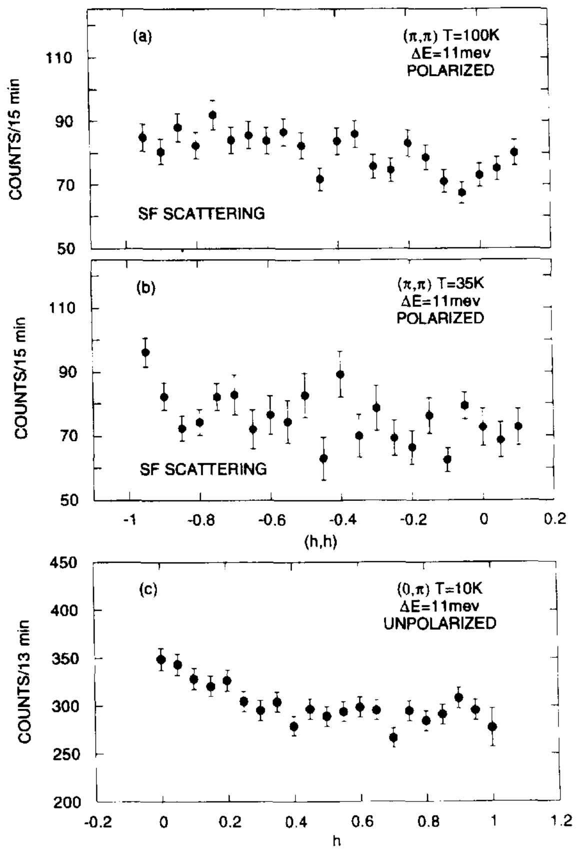


Fig. 5. Measurements made at 11 meV to sample the small magnetic scattering found at all energies in addition to the 40-meV peak. The measurements are for scans through (π, π) along the zone diagonal and parallel to the zone edge.

the two directions. The absolute $q$ value is $\sqrt{2}$ times larger for the (π, π) scan, confirming the square symmetry of the distribution. We note that the scattering intensity is nearly independent of temperature. The scattering distribution thus narrows upon cooling and increases in height in such a way that the intensity is nearly unchanged.

Fig. 2 shows that the bulk of the scattering at 100 K is rather featureless with intensity extending to low energies. Fig. 5 shows scans made at 11 meV in order to study the lower energy scattering. Scans at this energy are found to be relativity free of phonon scattering; however, polarized measurements are a necessity to determine the magnetic scattering. Fig. 5(a) shows a (π, π) polarized (HF) scan at 11 meV showing that the scattering is flat at 100 K, while Fig. 5(b) shows a similar result at 35 K. We note that the intensity is slightly smaller at 35 K, but detailed measurements using the HF–VF polarized technique are necessary to isolate this effect from temperature-dependent background effects. Fig. 5(c) shows a nonpolarized (0, π) scan at 11 meV. If any structure existed similar to that observed for $La_{1-\delta}Sr_{\delta}CuO_4$ [5], it would be apparent in this scan. However, we find the scan again to be flat. Since this scan passes through the point (π, π) as do the scans shown in Figs. 4(a) and (b), the intensity must be identical in these directions at least at 100 K, as all scans show no structure within the error of measurement.

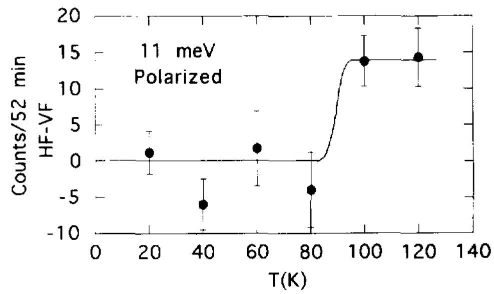


Fig. 6. Temperature dependence of the scattering at (π, π) for an energy transfer of 11 meV. The measurements are HF–VF polarized results which isolate only the magnetic scattering. Several measurements were averaged together, resulting in the error bars shown.

In order to determine the magnetic contribution to the scattering HF–VF polarized measurements have been made at (π, π) at 11 meV. Fig. 6 shows the temperature dependence of the magnetic scattering. A small but observable contribution is found at 100 K so that a uniform magnetic background is found at this temperature. As the temperature is lowered, this scattering is found to disappear. No scattering is observed at the lowest temperatures within the experimental error. Polarized measurements are absolutely essential for this measurement, as even though the nonmagnetic scattering is relatively small, it is about 250 counts at 11 meV on the scale of the figure. The beam polarization was monitored through the superconducting transition and found not to be affected adversely. The temperature dependence of the susceptibility is similar to that observed in NMR spin-lattice relaxation-time measurements for the planar Cu sites [6]. However, the large enhancement found for the Cu sites relative to the O sites may be more difficult to explain given the flat nature of the scattering. Of course, much of reciprocal space remains unexplored, and sharp structure may occur that has not yet been found.

We conclude our discussion of neutron results for Y123 with a brief mention of recent measurements of the lattice dynamics. Earlier measurements using neutron resonance absorption spectroscopy (NRAS) had shown that the Cu $a$–$b$ plane modes displayed an anomalous softening at a temperature slightly higher than the

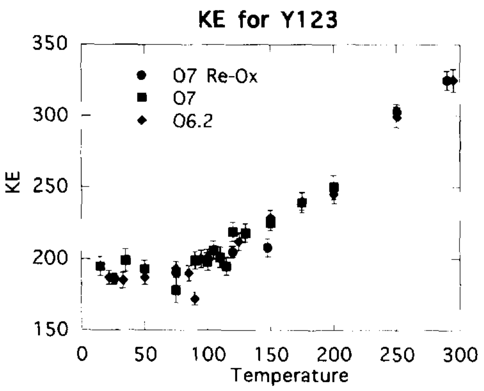


Fig. 7. Kinetic energy of the Cu phonons as a function of temperature. The square points are for the $O_7$ composition and the diamond points for $O_{6.2}$. The round points are for the sample reoxygenated to the $O_7$ composition.

superconducting transition for $Bi_2Sr_2CaCu_2O_8$ [7]. The NRAS measurements measure the kinetic energy (KE) of the Cu phonons. The KE is given by the integral of the Cu phonon density of states weighted by the phonon energy. The measurement examines the Cu phonons in all directions in the *a–b* plane and is more sensitive to the higher-energy phonons. The $Bi_2Sr_2CaCu_2O_8$ measurement and the presumed observation of large changes in the ion channeling for $ErBa_2Cu_3O_7$ [8] near $T_c$ suggested that phonons might play an important role in the superconductivity. We have now made NRAS measurements for Y123 for both $O_7$ and $O_6$ compositions. The new measurements show no change in the Cu KE at $T_c$ and no substantial softening of the phonons above $T_c$, as shown in Fig. 7. The phonon behavior found for $Bi_2Sr_2CaCu_2O_8$ is thus not essential for superconductivity. One interesting feature found in the NRAS measurements for both Y123 and $Bi_2Sr_2CaCu_2O_8$ is the lack of any drop off in the Cu KE below $T_c$. This shows that the Cu phonons must harden below $T_c$, which is opposite to the behavior expected for a conventional explanation of the superconductivity in terms of phonons. This of course provides no proof that phonons are not of primary importance for high-$T_c$ superconductivity but does diminish direct evidence that this is the case.

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