Comment on “Magnetic Order in the Pseudogap Phase of High-\textit{T}_c Superconductors”

In a recent Letter, Fauqué \textit{et al.} \cite{1} reported the detection of a novel magnetic order in YBa$_2$Cu$_3$O$_y$ (YBCO) near the pseudogap transition temperature $T^*$ by polarized neutron diffraction. They remark that this magnetic order has not been clearly identified by local probes and, in particular, by muon spin resonance ($\mu$SR). The purpose of this Comment is to point out that this is untrue, and together with the more recent detection of broken time reversal symmetry by polar Kerr effect measurements \cite{2}, there are now three very different kinds of experiments that provide evidence for this magnetic transition.

The onset of weak static magnetism near $T^*$ was in fact first detected in YBCO by zero-field (ZF) $\mu$SR \cite{3}. A subsequent study \cite{4} revealed correlations with charge inhomogeneities and structural changes that may play a role in stabilizing the magnetism. It has already been mentioned in Ref. \cite{2} that the polar Kerr effect and ZF-$\mu$SR measurements show similar magnetic onset temperatures for $y = 6.67$ and $y = 6.95$ single crystals. However, since the hole doping $p$ in the CuO$_2$ layers of YBCO not only depends on the oxygen content $y$, but also on the degree of oxygen ordering in the CuO chains, a proper comparison of the data from different techniques should be between samples with the same value of $p$. In Ref. \cite{3}, $p$ was calculated from the superconducting transition temperature $T_c$ using an empirical parabolic equation deduced from data on La$_{2-x}$Sr$_x$CuO$_4$ \cite{5}. Recently, a more accurate relationship between $p$ and $T_c$ has been established for YBCO that properly accounts for the suppression of $T_c$ near $p=1/8$ \cite{6}.

Figure 1 shows a comparison of the magnetic onset temperatures identified by the three different techniques, where the appropriate empirical relationship from Ref. \cite{3} has been used to determine $p$ for all data sets. It is reasonable to conclude from this plot that there is a single magnetic transition—\textit{i.e.} the magnetism detected earlier by ZF-$\mu$SR originates from the same source as the magnetic order detected by polarized neutron diffraction. While the neutron data is consistently above the ZF-$\mu$SR and polar Kerr effect data, Fig. 1 does not account for the transition widths $\Delta T_c$ ($\Delta p$), which are typically broader in the larger neutron samples.

The size of the local fields $B_{loc}$ detected by ZF-$\mu$SR depends on the type of magnetic order and the muon stopping sites. For $y = 6.95$, nearly all of the muons stop at a distance of $\sim 1$ Å from a chain oxygen \cite{6} at the position (0.15(1), 0.44(1), 0.071(1)) \cite{9}, whereas $\sim 1/3$ of the muons stop near an apical oxygen for $y = 6.67$. Assuming either the orbital current pattern or spin model displayed in Fig. 3 of Ref. \cite{1}, a simple dipolar-field calculation yields $B_{loc} \leq 130$ G/\textmu B at the chain oxygen site. Fauqué \textit{et al.} report an ordered magnetic moment of 0.05 to 0.1 \textmu B that decreases with increasing $p$ for $p \sim 0.09$ to 0.135. Consequently, for $y = 6.95$ ($p = 0.16$) a field of less than 6.5 G should be detected by ZF-$\mu$SR. This is not inconsistent with the measured characteristic field of $\sim 0.3$ G \cite{3}, especially since: (i) the proposed orbital and spin models do not account for the angle of $45 \pm 20^\circ$ the ordered moment makes with the $c$ axis \cite{1,7}, and (ii) the relaxation rate of the ZF-$\mu$SR signal is sufficiently weak that one cannot say (even from the other techniques) whether the magnetic order occurs in the full sample volume. If it does not, then the ZF-$\mu$SR experiments give a lower limit for the static local field in the magnetic regions.

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