Magnetic Excitations of the 2-D Sm Spin Layers in Sm(La,Sr)CuO$_4$

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Received 12 June 2005; revised 13 June 2005; accepted 14 June 2005

Abstract
We present specific heat and susceptibility data on Sm(La,Sr)CuO$_4$ in magnetic fields up to 9 T and temperatures down to 100 mK. We find a broad peak in specific heat which is insensitive to magnetic field at a temperature of 1.5 K with a value of 2.65 J/mol K. The magnetic susceptibility at 5 T continues to increase down to 2 K, the lowest temperature measured. The data suggest that the Sm spin system may be an ideal realization of the frustrated Heisenberg antiferromagnet on the square lattice.

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PACS: 75.40.Cx

Keywords: frustration; Heisenberg antiferromagnet; specific heat; cuprate; Sm

1. Introduction

The ideally frustrated 2-D Heisenberg antiferromagnet with first ($J_1$) and second ($J_2$) nearest neighbor interactions on the square lattice has been heavily studied theoretically,[1] but lacks few good examples in nature. For small $J_2/J_1$ the system orders into a Néel state, while for large $J_2/J_1$ one expects collinear order. At $J_2/J_1 \approx 0.5$ a spin liquid state whose properties are not well known is expected. Experimentally, the best examples of the spin 1/2 frustrated Heisenberg antiferromagnet on the square lattice occur in the vanadates, such as Li$_2$VO(Si,Ge)O$_4$,[2] VOMoO$_4$,[3] and Pb$_2$VO(PO$_4$)$_2$[4] where it is believed that $J_2/J_1 > 1$.

Here we report preliminary thermodynamic measurements on a single crystal cuprate Sm(La,Sr)CuO$_4$. By alternately stacking SmO and (La,Sr)CuO$_3$ layers this so called $T^*$ structure of the cuprates possesses 2-D Sm spin layers which are well isolated from one another.[5,6]

2. Results

Figure 1 presents raw specific heat data from a quasiadiabatic heat pulse method for Sm(La,Sr)CuO$_4$. At these temperatures the phonon contribution which becomes dominant above $\sim$ 10 K is negligible. There is a peak at $T_{\text{max}} = 1.5$ K with a value of $C(T_{\text{max}}) = 2.65$ J/mol K. The low temperature ($T < 0.2$ K) specific heat is the sum of a magnetic contribution and a nuclear Schottky contribution. We subtract the nuclear Schottky contribution that we model as the sum of a constant quadrupolar term and a dipolar term subject to Zeeman splitting: $C_{\text{nuc}}(T, H) = (0.0041 \text{ J K/mol} + 1.3 \times 10^{-5} H^2 \text{ J K/mol T}^2)/T^2$. The resulting magnetic contribution to the specific heat is shown in figure 2. Note that there remains a low temperature upturn, which is suppressed with increasing magnetic field, but no clear long range magnetic order is observed down to 100 mK.

The zero field cooled susceptibility shows a superconducting transition at 15 K. By applying a field of 5 T in the ab-plane the evidence for superconductivity is suppressed, and the susceptibility continues to rise down to 2 K, the lowest temperature measured. A Curie-Weiss plus constant fit to room temperature allows us to extract a background paramagnetic contribution $\chi_0 = 2.4 \times 10^{-6}$ emu/gm. The remaining signal at low temperature is attributed to the susceptibility of the Sm spins and a Curie-Weiss fit below 10 K gives $\Theta_{\text{CW}} = -4.5$ K.

3. Discussion

In the absence of frustration, the magnetic susceptibility should show a peak at $0.935 J$[7] where $J$ can be deter-
specific heat

the presence of frustration. The small peak value of the

ingation is playing a key role in the Sm spin dynamics. Know-

mined by the low temperature Curie-Weiss fit. Therefore, we have $T_{\text{max}}/\Theta_{\text{CW}} < 0.45$ which is strong evidence for the presence of frustration. The small peak value of the specific heat $C(T_{\text{max}}) = 0.32$ R, also suggests that frustration is playing a key role in the Sm spin dynamics. Knowing $C(T_{\text{max}})$ and $T_{\text{max}}$ we can use the work of Misguich, Bernu, and Pierre to solve graphically for $J_1$ and $J_2$.\cite{8} The two solutions are $J_2/J_1 = 2.0 \pm 4.8$ K $= 0.42$ and $J_2/J_1 = 3 \pm 3$ K/3 K $= 1$, which indeed places this system very close to the spin liquid regime. Meanwhile, the high temperature expansion of the $J_1$-$J_2$ model predicts that the magnetic excitations should fall off as $C_{\text{mag}} \approx 3J_2^2R/T^2$ where $J_{2D} = (J_1^2 + J_2^2)/2$ and $R = 8.314$ J/mol K. By assuming that the phonon contribution to the specific heat varies as $T^3$ up to 10 K, we can determine $J_{2D}$ by the $T=0$ linear extrapolation from a plot of $CT^2$ versus $T^5$ as done in the inset of figure 2. We find $J_{2D} \approx 2.4$ K. This value is roughly a factor of 2 too small for either graphical solution found using the work of reference \cite{8}. The graphical solution also appears to over estimate $J_1$ and $J_2$ when considering that the susceptibility also gives us $J_1 + J_2 = \Theta_{\text{CW}} = 4.5$ K. These small discrepancies might be reconciled if there is an additional mechanism, aside from a simple frustration model, that reduces the peak height in the specific heat. The graphical solutions could then lean towards smaller $J_1$ and $J_2$, with $J_2/J_1 > 1$. Whether or not additional longer range interactions, such as the RKKY interaction which could be mediated through the CuO$_2$ conduction layers, could achieve this remains to be seen.

The low temperature upturn in $C/T$ in figure 2 may indicate the onset of ordering either from 3-D coupling or an Ising like transition expected in the limit that $J_2/J_1$ is large.

We should also caution that this system has the obvious added complication of being embedded in a high temperature superconductor, with $T_c(H = 0) = 15$ K as determined from a susceptibility measurement. While this fact could be used to extract the magnetic spectrum via transport measurements,\cite{9} it may also have a significant effect on the Sm-Sm exchange interaction as observed previously in several other cuprates containing rare-earth elements within the charge reservoir layers.\cite{10}

4. Acknowledgements

We are very grateful to C. Batista for fruitful discussions. Work at Los Alamos was performed under the auspices of the US DOE.

References

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