Evidence for an incommensurate magnetic resonance in $La_{2-x}Sr_xCuO_4$

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We study the effect of a magnetic field (applied along the *c* axis) on the low-energy, incommensurate magnetic fluctuations in superconducting $La_{1.82}Sr_{0.18}CuO_4$. The incommensurate peaks at 9 meV, which in zero field were previously shown to sharpen in **q** on cooling below T_c [T. E. Mason *et al.*, Phys. Rev. Lett. **77**, 1604 (1996)], are found to broaden in **q** when a field of 10 T is applied. The applied field also causes scattered intensity to shift into the spin gap. We point out that the response at 9 meV, though occurring at incommensurate wave vectors, is comparable to the commensurate magnetic resonance observed at higher energies in other cuprate superconductors.

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I. INTRODUCTION

It has been observed in a variety of cuprate superconductors[1–5] that the inelastic magnetic scattering is enhanced below the superconducting transition temperature T_c at a particular energy E_r commonly referred to as the magnetic resonance energy. The "resonant" magnetic scattering is found to be centered at the antiferromagnetic wave vector and to have a rather narrow width in energy. The ratio E_r/kT_c is observed to be in the range 5–6.

One apparently anomalous system is $La_{2-x}Sr_xCuO_4$. To the best of our knowledge,[6] no one has identified a commensurate resonant response in this system by neutron scattering; nevertheless, when certain theoretical interpretations of the optical conductivity[7] and angle-resolved photoemission[8] are applied to measurements on $La_{2-x}Sr_xCuO_4$,[9,10] they seem to imply a resonance at an energy of roughly 40 meV. On the other hand, Mason and coworkers[11,12] found, for samples near optimum doping, an enhancement of magnetic scattering below T_c at *incommensurate* wave vectors and occurring for energies centered at about 9 meV. A concomitant narrowing in **q** width was also observed. It seems possible that this effect corresponds to the commensurate resonance seen in other cuprates.

To test the connection with the resonance phenomenon, it is desirable to perform further characterizations. One signature of the resonant magnetic scattering in underdoped $YBa_2Cu_3O_{6+x}$ is that the resonant scattering is reduced in amplitude by application of a uniform magnetic field.[13] Here we study the effect of a field on the incommensurate scattering in a slightly overdoped crystal of $La_{1.82}Sr_{0.18}CuO_4$. We find that, below T_c, the applied field reduces the peak intensity of the incommensurate scattering at 9 meV, thus providing support for associating the enhanced incommensurate scattering with the commensurate resonance response found in other cuprates.

There has also been considerable recent interest in the impact of an applied field on the magnetic scattering at lower energies. In particular, an applied field has been found to enhance elastic incommensurate scattering in underdoped samples,[14–17] and to induce inelastic scattering within the spin gap of an optimally doped sample.[18] For our slightly overdoped sample, it appears that the field causes weight to shift into the gap from higher energy, causing the frequency dependence to become more like that of the normal state just above T_c. These results are compared with a recent study[19] of Zn-doped $La_{1.85}Sr_{0.15}CuO_4$.

II. EXPERIMENTAL DETAILS

The experiment was performed on triple-axis spectrometer IN22 at the Institute Laue Langevin, which is equipped with a vertically focusing monochromator and a double-focusing analyzer of pyrolytic graphite, using the (002) reflection. No collimators were used, but cadmium masks were placed as close as possible to the sample (just outside of the magnet) to limit the beam size. We worked in fixed-E_f mode, with $k_f = 2.662$ Å^{-1} and a PG filter after the sample.

The sample was an array of four crystals grown at Kyoto University and coaligned in an aluminum holder. The total crystal volume was approximately 1.5 cm^3. Magnetic susceptibility measurements indicated that $T_c \approx 37$ K. These crystals are similar to, but distinct from, a sample of the same composition used in recent study of the spin gap.[20] For the present sample, the tetragonal-to-orthorhombic structural transition is at 118 K, whereas the transition is at 111 K for the previous sample. The higher transition temperature corresponds to a slightly lower Sr content.

The crystals, oriented with the [001] direction vertical, were mounted in a 12-T split-coil, vertical-field magnet. Thus, the applied field was along the *c* axis, and we could study scattering within the $(hk0)$ zone. (The [100] direction was aligned in the horizontal scattering plane, but the [010] direction was tilted out of plane by $\sim 2°$.) We made use of an orthorhombic unit cell with $a \approx b = 5.316$ Å.

For scans as a function of energy at fixed **Q**, we should, in principle, correct the intensities for energy-dependent counting-time errors due to the presence of harmonics in the

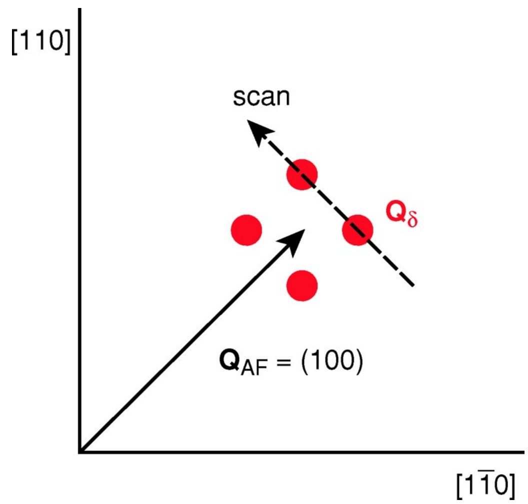

FIG. 1. (Color online) Sketch of the $(h,k,0)$ zone of reciprocal space, indicating the positions of the incommensurate magnetic wave vectors $\mathbf{Q}_\delta$, which are split about the antiferromagnetic wave vector $\mathbf{Q}_{\mathrm{AF}}$ denoted by the solid arrow. The dashed arrow indicates the path along which constant-energy scans were performed, $\mathbf{Q}=(1+\delta,k,0)$.

beam that reaches the incident-beam monitor (see Chap. 4, Sec. 9, in Ref. 21). A correction factor is known for instruments at the reactor face; however, IN22 is at the end of a thermal guide, which should reduce the relative intensities of harmonics. As we have not measured the harmonic content of the incident beam, we are not able to make the proper correction (which, at most, would involve a 20% effect over the measured energy range). This situation will have no impact on the conclusions of our analysis, which focuses on the variations of the inelastic signal with temperature and applied field; however, this effect, together with the coarser resolution used here, could be responsible for minor differences from the previous study.[20]

III. RESULTS

The low-energy magnetic scattering in $La_{1.82}Sr_{0.18}CuO_4$ is characterized by peaks at four incommensurate points about the antiferromagnetic wave vector, $\mathbf{Q}_{\mathrm{AF}}$. For a CuO_2 layer with a square lattice, these peaks would be indexed as $(\frac{1}{2}\pm\delta,\frac{1}{2})$ and $(\frac{1}{2},\frac{1}{2}\pm\delta)$, with $\delta=0.13$. In the orthorhombic unit cell which we will use in this paper, the coordinates are rotated by 45°, becoming $\mathbf{Q}_\delta=(1+\delta,\pm\delta)$ and $\mathbf{Q}'_\delta=(1-\delta,\pm\delta)$, as shown in Fig. 1. Because of time constraints, most of the measurements involved measuring the scattered intensity at the two peak positions $\mathbf{Q}_\delta$ and at background positions, $\mathbf{Q}_{\mathrm{b}}=(1+\delta,\pm0.4)$ and $\mathbf{Q}_0=(1+\delta,0)$, with a typical counting time of 15 min per point. (The actual measurements were done with $\delta=0.12$, rather than 0.13; the difference is not significant for these measurements.) The background measurements were found to be essentially independent of field, but slightly temperature dependent (and, of course, energy dependent). To improve the statistics, the background measurements at each energy were fit to a simple, monotonic function of temperature. To obtain the net intensity at $\mathbf{Q}_\delta$, the fitted background was subtracted from the average of the measurements at the two peak positions.

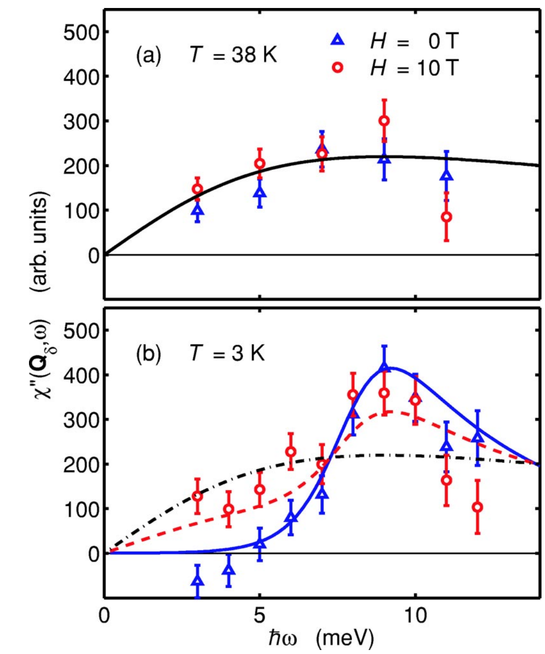

FIG. 2. (Color online) Measurements of $\chi''(\mathbf{Q}_\delta,\omega)$, in arbitrary units, at (a) $T=38$ K, just above T_c, and (b) $T=3$ K. In both panels, the triangles (circles) denote measurements at $H=0$ T ($H=10$ T). The lines through the data are explained in the text.

Figure 2 shows the energy dependence of the imaginary part of the dynamic susceptibility χ'' at $\mathbf{Q}_\delta$ measured at temperatures of 3 K and 38 K for zero field and $H=10$ T. χ'' was obtained by multiplying the net intensity by $1-\exp(-\hbar\omega/kT)$. At $T\approx T_c$ [Fig. 2(a)], the differences in χ'' with and without a field are small, and probably due to statistics. The line through the data points corresponds to

$$\chi''_0=A_0\frac{\hbar\omega\Gamma}{(\hbar\omega)^2+\Gamma^2}, \tag{1}$$

with $\Gamma=9$ meV.

At $T\ll T_c$, Fig. 2(b), we see a definite systematic difference between zero field and 10 T measurements. Applying the field tends to introduce signal within the gap and to decrease the signal above the gap. The solid curve through the zero-field data corresponds to the phenomenological form

$$\chi''_{\mathrm{sc}}=A_1\chi''_0[F_+(\omega)+F_-(\omega)]\left(\frac{\Delta_s}{\hbar\omega}\right)^2, \tag{2}$$

where χ''_0 (dot-dashed line) is from Eq. (1) and

$$F_\pm(\omega)=\tanh\left(\frac{\hbar\omega\pm\Delta_s}{\gamma}\right), \tag{3}$$

with $\Delta_s=8$ meV, $\gamma=1.5$ meV, and $A_1=1.5$. The dashed curve, which roughly describes the in-field data, is given by

$$\chi''=0.5\chi''_{\mathrm{sc}}+0.5\chi''_0, \tag{4}$$

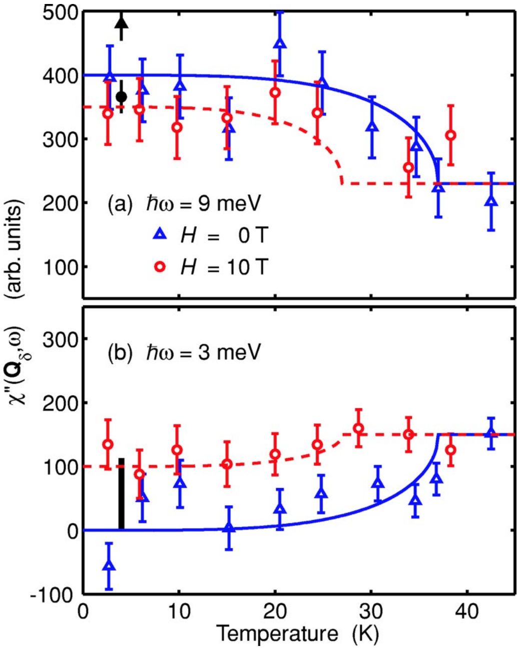

FIG. 3. (Color online) Temperature dependence of $\chi''(\mathbf{Q}_\delta,\omega)$ measured at excitation energies of (a) 9 meV and (b) 3 meV. In both panels, the triangles (circles) denote measurements at $H=0$ T ($H=10$ T). The lines through the data are explained in the text. The two filled symbols in (a) correspond to the fits in Figs. 4(c) and 4(d). The vertical bar in (b) corresponds to the fit of the intensity difference in Fig. 4(b).

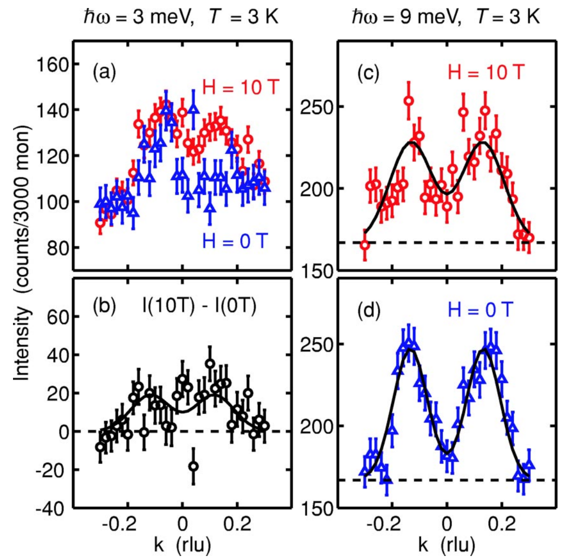

FIG. 4. (Color online) Constant-energy scans measured along the direction indicated by the dashed arrow in Fig. 1. All measurements are at 3 K; scans in (a) and (b) are for $\hbar\omega=3$ meV, and (c) and (d) are for $\hbar\omega=9$ meV. In (a), (c), and (d), triangles (circles) denote scans at $H=0$ T ($H=10$ T); (b) shows difference between scans from (a). Lines are fits to symmetric Gaussian peaks, as discussed in the text. The dashed lines in (c) and (d) indicate the background determined by averaging measurements at $k=\pm 0.4$ for field on and off at five temperatures up to 20 K.

where χ_0'' corresponds to the curve in Fig. 2(a) at 38 K. The curves are intended to be suggestive guides to the eye, rather than perfect fits to the data.

The temperature dependence of χ'' at 3 meV and 9 meV is shown in Fig. 3. At 3 meV, the in-field data are systematically finite and higher than the zero-field data for $T<T_c$. At 9 meV, the in-field signal is reduced compared to zero field. The curves are intended as suggestive guides to the eye, using a BCS-like function, $\sqrt{1-(T/T_c)^4}$. In zero field, the measured T_c is 37 K (solid lines), while for $H=10$ T, we estimate $T_c=27$ K from the magnetization study of Li *et al.*[22]

In their study of field effects on underdoped $YBa_2Cu_3O_{6+x}$, Dai *et al.*[13] argued that the resonant response is a measure of superconducting coherence. The onset of coherent superconductivity is reduced by the applied field, so that one would expect the onset of 9-meV signal enhancement and 3-meV signal reduction to follow $T_c(H)$. Our measurements seem to be consistent with such a scenario; however, there are insufficient data points at higher temperatures and the error bars are too large to allow one to draw any firm conclusions regarding a quantitative correlation with $T_c(H)$.

Figure 4 shows constant-energy scans along $\mathbf{Q}=(1+\delta,k)$ (see dashed line in Fig. 1) for $\hbar\omega=3$ meV on the left and 9 meV on the right, all measured at $T=3$ K. The 3-meV scans have a strongly **q**-dependent background contribution that makes it difficult to analyze the raw data. It is more practical to look at the difference (high field−zero field), shown in (b). The difference is consistent with a symmetric pair of broad peaks at $k=\pm 0.12(2)$. The peak amplitude of 19(3)/3000 monitor counts is consistent with the results in Figs. 2(a) and 3(b) (see the vertical bar in the latter), thus confirming the growth of low-energy incommensurate scattering due to the presence of the field.

The 9-meV scans appear to have a more uniform background. The curves represent fits with symmetric Gaussian peaks. In zero field, the peaks are at $k=\pm 0.134(3)$ with amplitude $=80(4)$ and full width at half maximum (FWHM)$=0.148(7)$; in 10 T the fit gives $k=\pm 0.131(5)$, amplitude $=61(4)$, and FWHM$=0.183(10)$. Applying the field broadens the peaks and reduces the amplitude; the amplitude change is consistent with Figs. 2 and 3(a) (see the filled symbols in the latter).

In their study of $La_{1.86}Sr_{0.14}CuO_4$, Mason *et al.*[11] observed at 9 meV an enhancement of intensity and a narrowing in **q** when cooling through T_c, which they discussed as a coherence effect associated with superconductivity. We find that application of a 10 T field has the opposite effect: the magnetic susceptibility is reduced, and the q width is increased. Again, this seems to be consistent with a reduction in superconducting coherence due to the field.

IV. DISCUSSION

A. Resonance feature

In our slightly overdoped sample, we find that the application of a uniform magnetic field parallel to the c axis causes a reduction of χ'' at the energy of the peak (~ 9 meV). The signal at this energy is otherwise enhanced on cooling below T_c. This behavior is reminiscent of the field-induced decrease in the resonance peak observed[13] in underdoped $YBa_2Cu_3O_{6+x}$, the main difference being that the response occurs at an incommensurate, rather than commensurate, wave vector in $La_{2-x}Sr_xCuO_4$. We note that in the original analysis of the zero-field enhancement of the incommensurate signal, Mason *et al.*[11] suggested that the increase in signal below T_c came from the superposition of an extra contribution that is very narrow in q. Lacking a physical motivation for such a decomposition of the excitations, we believe it is more reasonable to view the changes below T_c as a modification of the excitations that exist in the normal state.

In terms of the relative energy scale, the ratio E_r/kT_c observed for other cuprates[1–5] is found to lie in the range 5–6, as mentioned in the Introduction. If we identify $E_r \approx 9$ meV for our sample, then $E_r/kT_c \approx 3$. Relative to Δ_0, the maximum of the superconducting energy gap, E_r, is observed to always be less than $2\Delta_0$, and generally not much greater than $\sim\Delta_0$. For $La_{2-x}Sr_xCuO_4$ with $x=0.18$, $\Delta_0 \approx 10$ meV, based on tunneling[23] and Raman scattering studies,[24] so E_r/Δ_0 is consistent with that for other systems.

Regarding energy scales, it is interesting to note that in a study of $YBa_2Cu_3O_{6+x}$ with $x=0.51$ and $T_c=47$ K, Rossat-Mignod *et al.*[25] observed a spin gap of ~ 4 meV in the superconducting state together with an enhancement of χ'' (with respect to the normal state) peaked at ~ 7 meV. These energies are comparable to those in our $La_{2-x}Sr_xCuO_4$ sample. In more highly doped $YBa_2Cu_3O_{6+x}$, where the attention has tended to focus on the commensurate resonance feature, we note that the enhancements of χ'' at incommensurate wave vectors (for $E \neq E_r$) have also been observed.[26–28]

The measured energy width (full width at half maximum) of the 40-meV resonance peak in $YBa_2Cu_3O_7$ is limited by the resolution width of 5 meV,[29] whereas the width of the 33-meV resonance peak in the ortho-II phase is slightly larger than the resolution at 7 meV.[30] The width of the peak in our $La_{1.82}Sr_{0.18}CuO_4$ sample is roughly 3 or 4 meV, depending on how one measures it. It is comparable to the width of the low-energy resonance observed by Rossat-Mignod *et al.*[25] in their $YBa_2Cu_3O_{6+x}$ sample with $T_c=47$ K.

There has been a variety of theoretical approaches to the magnetic resonance and its energy and q dependence. From the perspective of SO(5) theory, a model in which commensurate antiferromagnetism competes with d-wave superconductivity, a magnetic resonance is predicted to appear precisely at $\mathbf{Q}_{AF}$.[31,32] It corresponds to a collective mode in the particle-particle channel, to which neutrons cannot couple except in the superconducting state where coupling is enabled by the coherent mixture of particles and holes in the BCS condensate. While the theory has been extended to include (nontopological) stripes[33] and dispersion of the resonance,[34] the commensurate resonance appears to remain a central feature.

One alternative is to attribute the resonance to an excitation of antiferromagnetically coupled Cu spins.[35,36] In the normal state, interactions with the charge carriers cause the spin fluctuations to be strongly damped, while fluctuations with energies below $2\Delta_0$ become underdamped in the superconducting state. Since the q dependence of the spin fluctuations is generally chosen to match the experiment in this approach, it can be either commensurate[35,36] or incommensurate.[37]

The most common approach is to calculate the magnetic response of the charge carriers themselves in the particle-hole channel, which is then enhanced with the random-phase approximation.[38–45] Whether the calculated fluctuations are commensurate or incommensurate depends on the shape of the Fermi surface.[41,43,46] Using a model dispersion that gives a Fermi surface consistent with the results of angle-resolved photoemission spectroscopy (ARPES) for $YBa_2Cu_3O_{6+x}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$ yields a commensurate resonance peak.[46]

Calculations[41,43,45] for $La_{2-x}Sr_xCuO_4$ have generally used parameters corresponding to a Fermi surface that is more nearly nested along the direction of $\mathbf{Q}_{AF}$ than that considered for the bilayer cuprates; however, it has been argued[43] that the differences in models are not essential for obtaining the normal-state incommensurate structure in χ''. (We note that recent ARPES studies indicate that the Fermi surface for optimally doped $La_{2-x}Sr_xCuO_4$ is actually quite similar to that for the bilayer cuprates.[47]) In any case, a commensurate resonance feature is predicted[41,43] to appear below T_c; in particular, Kao *et al.*[43] predict the resonance peak to occur at 15 meV. While we must admit that we have not pushed our measurements quite this high in energy, the maximum at 9 meV observed at an incommensurate wave vector does not appear to be consistent with these calculations.

Some theorists have argued that there is a connection between the magnetic resonance peak and certain anomalous features seen in ARPES measurements, such as the "peak-dip-hump" structure[8,36,48] and the "kink" in the quasiparticle dispersion.[8,49] Eliashberg theory has been used to make a connection between the resonance and certain features in the optical conductivity.[7] (Theoretical arguments against such connections have also been made.[50]) Now, it happens that the same anomalous kink and optical conductivity features identified for $Bi_2Sr_2CaCu_2O_{8+\delta}$ are also observed for $La_{2-x}Sr_xCuO_4$.[9,10] To consistently interpret these features in terms of the magnetic resonance, one would have to infer a commensurate resonance at an energy of about 40 meV for $La_{2-x}Sr_xCuO_4$. Our identification of the incommensurate 9-meV feature as the analog of the resonant mode contradicts such an inference.

Finally, we note that the low-energy magnetic excitations in the normal state of $La_{2-x}Sr_xCuO_4$ look very much like those observed[51,52] in stripe-ordered $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$. In the latter system, one interprets the incommensurate excitations as spin waves of the magnetically ordered system. The differences for $La_{2-x}Sr_xCuO_4$ can be understood in terms of the fluctuations of a quantum-disordered system[53] with stripe correlations.[54] The magnetic excitations are certainly sensitive to the charge fluctuations; after all, from the stripe perspective, the incommensurability is the direct result of the spatially inhomogeneous distribution of the doped holes.[55–57] The generation of a spin gap, together with pairing of charge carriers, has been predicted based on a model that assumes the existence of stripes.[58] One certainly expects singlet-triplet excitations to appear above the spin gap.[53] A model for the magnetic resonance based on incommensurate spin waves has been proposed;[59] however, a naive comparison with spin-wave measurements in a stripe-ordered nickelate indicates that this model has some shortcomings.[60]

B. Field-induced signal in the spin gap

Neutron-scattering experiments on underdoped $La_{2-x}Sr_xCuO_4$ (Refs. 14 and 15) and on $La_2CuO_{4+\delta}$ (Refs. 16 and 17) have shown that the application of a magnetic field along the c axis at temperatures less than T_c can induce or enhance spin-density-wave order. While there has been a number of proposals for the induced correlations in magnetic vortex cores,[61–64] we believe that the most natural explanation involves the pinning of charge and spin stripes by vortices.[54,65–71] The observation that well developed charge and spin stripe order in $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ are not affected by the application of a magnetic field is consistent with this picture.[72]

In contrast to the underdoped regime, there is a spin gap in the superconducting state for optimally doped $La_{2-x}Sr_xCuO_4$.[12,73,74] The gap in the low-energy spin fluctuations indicates that the spin stripes are further away from the ordered state,[54,66,67] so it is not surprising that an applied magnetic field does not induce static correlations. Instead, Lake *et al.*[18] showed, on a sample with $x=0.163$, that applying a field induces a signal within the spin gap. Our results are generally consistent with theirs. One difference is that they observed an upturn in the low-energy (2.5 meV) in-field signal as the temperature decreased below $\sim$10 K, whereas we did not see such an upturn in our slightly overdoped sample.

The application of the magnetic field in the superconducting state introduces inhomogeneity associated with the vortices. The superconducting order parameter goes to zero at the center of each vortex, and the area over which the order parameter is strongly depressed is equal to $\pi\xi^2$, where ξ is the superconducting coherence length. The areal fraction corresponding to the vortex cores is equal to H/H_{c2}, where H_{c2} is the field at which the sample becomes completely filled by vortex cores. The resistivity studies of Ando *et al.*[75] indicate an H_{c2} of approximately 55 T at 3 K for $La_{2-x}Sr_xCuO_4$ with $x=0.17$, while the Nernst effect study of Wang *et al.*[76] suggests a low temperature H_{c2} of greater than 45 T for an $x=0.20$ sample. Taking $H_{c2}\approx 50$ T for our $x=0.18$ sample at 3 K, we find that, for our applied field of 10 T, $H/H_{c2}\approx 0.2$. Thus, 20% of the area is occupied by vortex cores.

We expect that the magnetic scattering associated with the vortex cores will be different from that due to the superconducting regions outside the cores. We have seen that applying the magnetic field at 3 K causes χ'' to change so that it appears closer to the normal state. Let us assume that applying a magnetic field large enough to suppress the superconductivity would yield a spectrum identical to that measured at 38 K. The measurements at 10 T can be roughly modeled as an average between normal-state and zero-field-superconductor signals. If the "normal-state" response came from just the vortex cores, then we would expect its weight to be just 20% instead of 50%. The larger normal-state response indicates that it must come from regions about 2.5 times the area of the vortex cores. This result is consistent with an estimate[77] for the relative area in which the resonance is suppressed in $YBa_2Cu_3O_{6.6}$. The idea of a halo region extending beyond the vortex core was suggested by the scanning tunneling microscopy study of $Bi_2Sr_2CaCu_2O_{8+\delta}$ by Hoffman *et al.*[78] and discussed by Zhang *et al.*[65] A much larger halo region is required to explain the neutron-scattering measurements[14–17] of field-induced spin-density-wave order in underdoped $La_{2-x}Sr_xCuO_4$ and $La_2CuO_{4+\delta}$. Of course, our analysis of overdoped LSCO is based on an assumption for the high-field, low-temperature state that may be incorrect. Measurements with a local probe would be needed to reach an unambiguous conclusion.

We agree with Lake *et al.*[18] that the magnetic field induces a response that is closer to magnetic ordering; however, our interpretation of that induced response differs somewhat from theirs. They interpreted the induced response to be a mode within the spin gap, with a peak energy much lower than the peak energy found in the normal state above T_c. Our results show that changes occur at higher energies as well, so that the induced response is not restricted to the spin-gap region.

It is interesting to compare with a recent inelastic-neutron-scattering study[19] of Zn-doped $La_{2-x}Sr_xCuO_4$. In the muon-spin-rotation study of Nachumi *et al.*,[79] it was deduced that each Zn dopant reduces the superconducting carrier density by a fractional amount corresponding to a relative area equal to that of a magnetic vortex core. One might then expect that the impact on spin excitations might be similar to that from vortices. Indeed, Kimura *et al.*[19] find that Zn doping introduces a component of spin fluctuations that extends into the spin gap of the non-Zn-doped $x=0.15$ parent material. The amount of signal within the spin gap grows with doping, and an elastic component becomes detectable at a Zn concentration of 1.7%. At that level of Zn, T_c has been reduced from 37 K to 16 K. That is a larger change in T_c than we are able to accomplish in our $x=0.18$ sample with experimentally achievable magnetic fields. Of course, our sample is on the metallic side of the insulator-to-metal crossover identified by Boebinger *et al.*[80] using applied magnetic fields of 61 T, so that it seems unlikely that we would be able to induce static spin stripe order in it simply by suppressing the superconductivity.

To avoid confusion, we should note that there are differences in the way that we and Kimura *et al.*[19] have presented the inelastic results. In presenting energy and temperature dependence, we have shown χ'' measured at a particular $\mathbf{q}$ point, whereas Kimura has plotted χ'' integrated over $\mathbf{q}$. Variations in q width of the inelastic peaks can cause the dependences of these quantities on temperature, energy, etc., to be slightly different. Indeed, looking at the measurements at $\hbar\omega=9$ meV and $T=3$ K in Figs. 4(c) and 4(d), we see a drop in the peak intensity on applying the field; however, the peak area changes much less, since the width grows.

Vojta *et al.*[81] have shown that there is at least one theoretical difference between the effects of a Zn dopant and a vortex: substitution of a Zn atom for Cu effectively introduces a free spin. While these free spins can be detected by probes of the uniform spin susceptibility,[82] it is not clear that they should play the dominant role in the observed changes in inelastic scattering. It seems likely that the observed changes must come from a significant range about each Zn, and that they involve a slowing of stripe fluctuations in the vicinity of impurities, similar to the impact of vortices.

V. SUMMARY

We have studied the effect of a magnetic field, applied parallel to the c axis, on the low-energy magnetic fluctuations in slightly overdoped $La_{1.82}Sr_{0.18}CuO_4$. We observe that the enhancement of the incommensurate intensity at 9 meV for $T<T_c$ is reduced when the field is applied. Based on this result, we identify the 9-meV peak as a resonance feature in analogy with the commensurate resonance found in other cuprates. Field-induced signal is seen within the spin gap, consistent with an earlier study, and indicating that the applied field, which suppresses the superconductivity within vortex cores, also pushes the magnetic correlations closer to a stripe-ordered state. The intensity of the in-gap signal indicates that it must come from a region substantially larger than that of a vortex core.

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