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Effect of a magnetic field on the electron-boson spectral function of cuprate superconductors

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We have performed magneto-optical measurements on a series of high-T_c superconductors with magnetic field up to 18 T. Similar to previous reports in smaller fields, the results reveal that the optical constants, both in the normal and superconducting state, of several families of high-T_c cuprates are completely insensitive to the application of external magnetic field. These magneto-optical results seem to indicate that either the bosonic mode responsible for pairing is not magnetic in origin, or the charge carriers are not very strongly coupled to it. We discuss the results within the existing theoretical models.

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The nature of the collective boson mode responsible for superconductivity in the cuprates is currently the center of great controversy in the field. Two opposing views have been battling for supremacy. The older scenario, dating back to the early 90's, argues for spin-fluctuations as the pairing glue for high-T_c superconductivity.[1,2] More recently phonons have been put forward as a possible mediator for superconductivity in the cuprates.[3] The physical quantity that characterizes coupling between charge carriers and collective bosonic modes is a so-called Eliashberg electron-boson spectral function $\alpha^2F(\omega)$ and is one of the most important characteristics of a boson-exchange superconductor.[4] This function can be obtained from tunneling, photoemission (ARPES), or infrared (IR) spectroscopy.

Figure 1 shows our new zero-field IR data of underdoped $La_{1.875}Ba_{0.125}CuO_4$ (LBCO) single crystal with T_c=2.4 K. All the measurements were performed on a *cleaved* surface, in order to probe the intrisic response of CuO_2 planes, where superconductivity is thought to originate. Figure 1(a) displays the frequency dependence of zero-field reflectance $R(\omega)$ at 300 and 10 K (both above T_c=2.4 K). From $R(\omega)$ the optical conductivity $\sigma(\omega)=\sigma_1(\omega)+i\sigma_2(\omega)$ was then calculated using Kramers-Kronig transformation. The optical scattering rate $1/\tau(\omega)$ was obtained from the complex optical conductivity within a so-called "extended" Drude model:

$$\frac{1}{\tau(\omega)} = \frac{\omega_p^2}{4\pi}\,\mathrm{Re}\left[\frac{1}{\sigma(\omega)}\right], \qquad (1)$$

where ω_p is the conventional plasma frequency. The scattering rate spectra at 300 and 10 K are shown in Fig. 1(b). From $1/\tau(\omega)$ the electron-boson spectral function $\alpha^2F(\omega)$ was calculated within Midgal-Eliashberg formalism, using Allen's formula (at T=0 K)[5] and the recently developed inversion method[6]

$$\frac{1}{\tau(\omega)} = \frac{2\pi}{\omega}\int_0^\omega d\Omega(\omega-\Omega)\alpha^2F(\Omega). \qquad (2)$$

The spectral function $\alpha^2F(\omega)$ has characteristic shape [Fig. 1(c)], with a strong peak in the far-IR and significant contribution that extends throughout the mid-IR, up to several hundred meV. Similar spectral functions have been found in all families of cuprates for which IR data exist.[6,7] This high-frequency contribution to $\alpha^2F(\omega)$ indicates that phonons cannot be the sole origin of the spectral function, as typical phonon frequencies in the cuprates are limited to energies below about 100 meV. However phonons can contribute at lower frequencies, i.e., to the main peak. It is the nature of this peak that is at the center of ongoing debate.[3,8,9] Its energy is in the range of phonons, but also of magnetic excitations as probed by inelastic neutron scattering (INS).[10,11] These experiments have found a so-called "resonance" at certain energy at $\mathbf{k}=(\pi/2,\pi/2)$ in reciprocal space. At higher and lower energies the resonance splits into incommensurate peaks.[10,11] Application of magnetic field was found to suppress the resonance in $YBa_2Cu_3O_{6.6}$ (Ref. 12). In $La_{1.90}Sr_{0.10}CuO_4$ and $La_2CuO_{4+\delta}$, on the other hand, the application of magnetic field was found to enhance the incommensurate magnetic peaks.[13,14] The magnetic excitations in electron-doped $Nd_{1.85}Ce_{0.15}CuO_4$ are also sensitive to the application of magnetic field.[15]

If the peak in the spectral function $\alpha^2F(\omega)$ is indeed related to the resonance (or any other mode magnetic in origin) then the application of a magnetic field should also affect the charge dynamics. Principal limitations do not allow ARPES experiments to be performed in magnetic field. This leaves infrared spectroscopy (and possibly tunneling) as the experimental techniques to probe these effects. Lee *et al.* have recently studied magneto-optical response of two underdoped $YBa_2Cu_3O_x$ samples with x=6.50 and 6.65 (Refs. 16 and 17). Their results revealed that the optical constants of these two samples are completely insensitive to magnetic fields up to 7 T. Recent IR Hall measurements on YBCO and Bi2212, performed with min-IR lasers at several discrete frequencies between 900 and 1100 cm^{-1}, also did not detect any measurable variation of transmission with magnetic fields up to 8 T.[18,19] In this work we extend these magneto-optical measurements to several other cuprates families and to magnetic fields up to 18 T.

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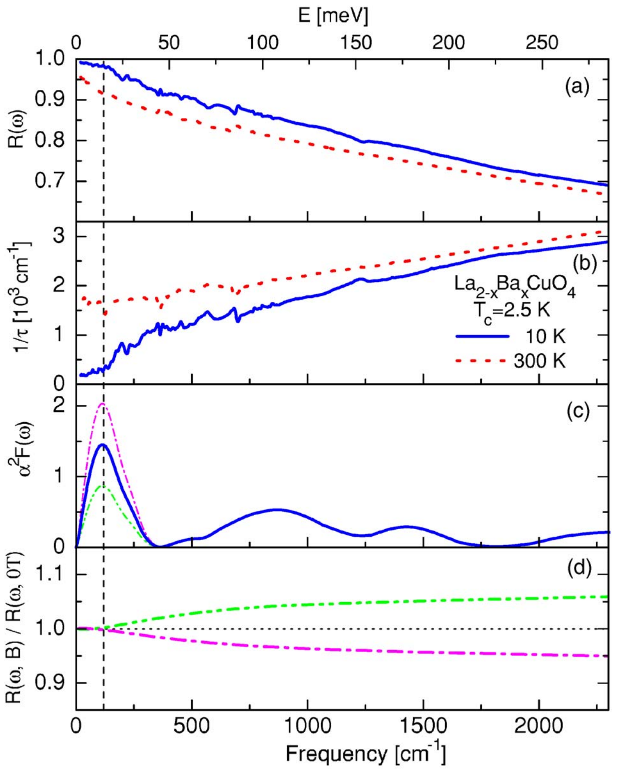

FIG. 1. (Color online) Optical constants of $La_{2-x}Ba_xCuO_4$ (LBCO) with $T_c=2.4$ K in zero magnetic field. (a) Reflectance $R(\omega)$ at 300 and 10 K. (b) The scattering rate $1/\tau(\omega)$ at 300 and 10 K. (c) Calculated electron-boson spectral function $\alpha^2F(\omega)$ at 10 K (full blue line) and the same function with the main peak suppressed (dash-dot-dot green line) and enhanced (dash-dot magenta line) by 40%. These modifications of $\alpha^2F(\omega)$ are intended to simulate the effect of external magnetic field. (d) Calculated reflectance ratio $R(\omega,B)/R(\omega,0\text{ T})$ with the intensity of the main peak suppressed (dash-dot-dot green) or enhanced (dash-dot magenta) by 40% [panel (c)]. The vertical dashed line indicates the position of the peak in $\alpha^2F(\omega)$ and the "kink" in $1/\tau(\omega)$. Note that below the peak calculated changes of reflectance are small, but are expected to grow monotonically above the peak.

In order to estimate the magnitude of field-induced changes and the possibility of observing those effects, we follow the analysis protocol proposed by Lee *et al.* (Refs. 16 and 17). First we change the intensity of the main peak in zero-field $\alpha^2F(\omega)$ by a certain amount (we either reduce it or enhance it) to simulate the possible effect of magnetic field. For the relative change of intensity we employed the relation $I/I_0=1-(B/B_{\text{char}})$ with $B_{\text{char}}=36$ T, as suggested in Ref. 12. As neutron-scattering measurements in magnetic field have only been performed on a few systems, we assumed the same relation for all our samples and in all fields up to 18 T. This equation gives about 20% suppression at 7 T, 30% in 10 T, 40% in 14 T, and around 50% at 18 T. Once the new spectral function is known, the whole procedure is reversed to obtain other optical constants, including the reflectance.

Figure 1(d) displays an example of these calculations. The intensity of the main peak in $\alpha^2F(\omega)$ was both reduced by 40% [dash-dot-dot green line in Fig. 1(c)] and enhanced by 40% [dash-dot magenta line in Fig. 1(c)]. We have then recalculated the optical constants and in Fig. 1(d) we display the corresponding reflectance ratios $R(\omega,B)/R(\omega,0\text{ T})$ for the two spectral functions in Fig. 1(c). The predicted changes of reflectance are fairly small in the far-IR part of the spectrum, but monotonically increase with frequency toward the mid-IR and appear to be measurable by state-of-the-art magneto-optical setups.[20]

We have performed extensive magneto-optical measurements on several families of high-T_c cuprates, including optimally doped $YBa_2Cu_3O_{7-\delta}$ (YBCO) 1.6-μm-thick film with $T_c=92$ K, several $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystals with different doping levels and T_c's, the underdoped $La_{1.875}Ba_{0.125}CuO_4$ sample mentioned above, and optimally doped $Nd_{1.85}Ce_{0.15}CuO_4$ (NCCO) single crystal with $T_c=23$ K. The measurement system consisted of a Fourier transform infrared (FTIR) spectrometer Bruker 113 coupled to an 18 T superconducting magnet at the National High Magnetic Laboratory (NHMFL). All field induced changes of reflectance $R(\omega,B)/R(\omega,0\text{ T})$ have been measured under the zero-field cooling conditions at $T=4.2$ K, in the frequency range between approximately 350 and 2300 cm^{-1} (43–285 meV) and in the fields up to 18 T. Magnetic field was applied perpendicular to CuO_2 planes and changes in the in-plane reflectance were monitored. For some samples we have extended the measurements into the far-IR down to 30 cm^{-1} (3.7 meV), but similar to previous studies,[16,17,21] no field-induced changes of reflectance were found in this part of the spectrum.

Figure 2 displays the reflectance ratios for YBCO film at several field values, all taken at 4.2 K. Figure 2(a) shows the ratio of two scans at zero field taken over a period of a few hours. This is a so-called "100% line" and is commonly used as a measure of drift in the system, which is the most serious challenge with mid-IR measurements.[20] The regions with poor signal-to-noise are caused by 60 cycle noise.[22] The other four panels display reflectance ratios $R(\omega,B)/R(\omega,0\text{ T})$ for B=7, 10, 14, and 18 T. The vertical dashed line marks the approximate position of the kink in reflectance,[23] with the biggest changes expected above that frequency. However within the error bars there is no field dependence of reflectance in the measured frequency interval. In particular, we do not observe any *systematic trends* in the data as the magnitude of the field changes.

Figure 3 shows the ratios $R(\omega,18\text{ T})/R(\omega,0\text{ T})$ at 4.2 K, for four different samples including YBCO film, Bi2212, LBCO, and NCCO single crystals. Again within the error bars there are no field induced changes of reflectance in any of the studied samples. Note that the LBCO sample had $T_c=2.4$ K and was therefore in the normal state at the measurement temperature (4.2 K). On the other hand, NCCO samples have $B_{c2}\simeq 7$ T,[15] and 18 T was therefore sufficient to completely destroy superconductivity. However in neither case did we observe any field induced changes. Several Bi2212 samples with different doping levels (both underdoped and overdoped) were also measured and in none of them were any field-induced effects detected.

The absence of any field-induced effects is puzzling and unexpected. The simplest explanation would be that the boson mode is not magnetic in origin, laying support for the

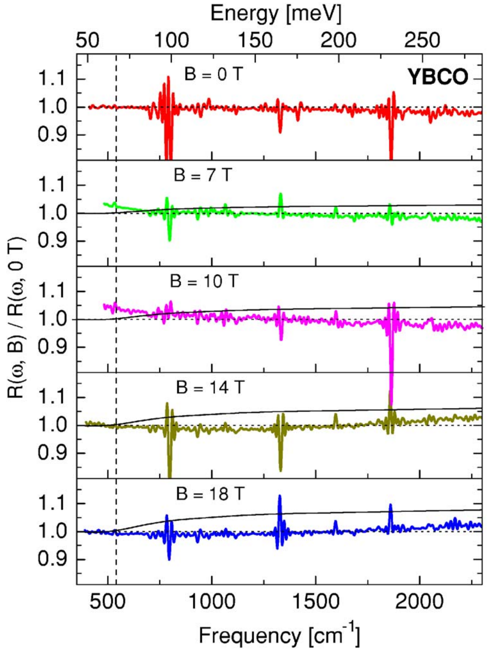

FIG. 2. (Color online) The magneto-optical results at 4.2 K for optimally doped YBCO 1.6 μm thick film with T_c=92 K and at several different magnetic field values between 0 and 18 T. The top panel displays a 100% line, which is commonly used to quantify the signal-to-noise ratio and temporal drift in the measurement system.[20] The other four panels show reflectance ratios $R(\omega,B)/R(\omega,0\ \text{T})$, with B=7, 10, 14 and 18 T. The vertical dashed line indicates the approximate position of the peak in $\alpha^2F(\omega)$ in zero field. The biggest changes in reflectance are expected above the frequency of the peak, but within the error bars there are no field-induced changes. Thin black lines are expected changes for each field value, based on the calculations described in the text.

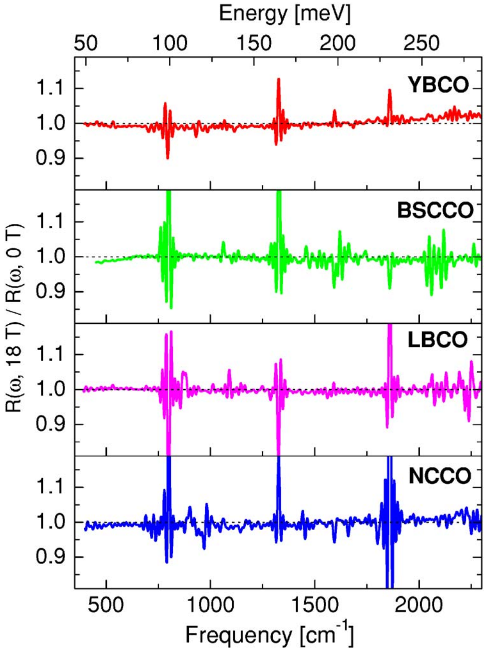

FIG. 3. (Color online) Magneto-optical ratios $R(\omega,B=18\ \text{T})/R(\omega,0\ \text{T})$ at 4.2 K for YBCO film (Fig. 2), Bi2212 single crystal, LBCO single crystal with T_c=2.4 K and NCCO single crystal with T_c=23 K. The biggest field-induced changes of reflectance are expected in the mid-IR part of the spectrum, however, within the error bars of this experiment, no changes are detected in either of the samples.

phonon mechanism of superconductivity. However as we mentioned above, the extended spectral range of $\alpha^2F(\omega)$ indicates that phonons cannot be the sole contributors. Alternatively one can argue that field effects are weaker than what electron-boson coupling theory predicts. In that case the reflectance changes must be within the error bars of the experiment. We have used the same experimental setup to measure field induced changes in the reflectance of graphite and were able to identify features as small as 1 – 2%.[24] Using the ±2% as the most conservative limits for the error bars, we can put an upper bound on the field induced changes in $\alpha^2F(\omega)$. Based on the electron-boson coupling calculations described above, we estimate that the relative change of the main peak in $\alpha^2F(\omega)$ in YBCO cannot be bigger than $\simeq$10% at 18 Tesla. These results clearly call for magneto-optical measurements in higher magnetic fields.

In summary, we have extended the magneto-optical measurements of Lee *et al.* (Refs. 16 and 17) to several other cuprate families and magnetic fields up to 18 T. Our results have revealed that, within the error bars of this experiment, there are no field-induced changes in the optical properties. Calculations yield an upper limit on the changes in the spectral function, which in optimally doped YBCO cannot be bigger than $\simeq$10% at 18 T. These results indicate that charge carriers in the cuprates might not be coupled to spin fluctuations as strongly as originally thought. One might also speculate that superconductivity in high-T_c cuprates is not of boson-exchange type and that alternative theoretical approaches must be developed for its understanding.

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