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A Phenomenological Study of Angle-Resolved Photoemission Spectra for High-T_c Superconductors

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Abstract

Using a phenomenological model for the normal state of high-T_c superconductors, we have analyzed the angle-resolved photoemission spectra, and compared our results with the MFL theory and other microscopic models as well as with the experiments. In contrast to the MFL theory we predict that there exists a narrow lower energy region near the Fermi surface showing the conventional Fermi liquid behavior, which needs to be approved by fine experiments in future.

In a few years ago, a lot of efforts have been made to understand the mechanism of high-T_c oxide superconductors. Up to now, however, we have gotten a little progress toward this target although extraordinary new developments have been made in some related fields called strongly correlated systems, e.g., quantum antiferromagnetism, Hubbard model etc.[1]. On the other hand, there have been great advances experimentally and theoretically for the investigation of their normal state properties[2]. All of us agree that the experimental observations from its electrical resistivity $\rho(T)$, optical conductivity $\sigma(\omega)$ and Raman scattering intensity $S(\omega)$ to the NMR rate $T_1^{-1}(T)$ and the Hall coefficient $R_H(T)$ show clearly anomalous characteristics of the normal state properties. It seems that these anomalies could not be described by a conventional Fermi liquid theory. Therefore, several non-Fermi liquid theories including microscopic and phenomenological ones have been proposed to explain the anomalous normal state properties. Among them are the Luttinger liquid model[3], the marginal Fermi-liquid (MFL) theory[4], the antiferromagnetic Fermi-liquid model[5], the nested Fermi-liquid model[6] and finally the spin bag model[7]. Comparing with other models, the MFL theory seems to be better due to its success of a unified correct description of all normal state properties. Moreover, its hypothesized expression for the polarizability $\chi(q,\omega)$ has further been approved in two limiting cases, i.e., $\omega/T \gg 1$ and $\omega/T \ll 1$, by recent neutron scattering experiments[8,9]. Although the MFL theory is rather successful, there are still some uncertainties in it. For example, the discontinuity of $\chi(\omega)$ at $\omega \sim T$ in the theory is an artificial assumption, and the biggest shortcoming of the theory. The neutron scattering experiments demonstrate that the $\chi(\omega)$ should be a continuous function of ω and there is no discontinuity at all[8,9]. In order to remedy this defect in the MFL theory we proposed in an earlier paper[10] another phenomenological model about the polarizability $\chi(\omega)$ from the experimental Raman scattering intensity $I(\omega)$ in the normal state. In our model we select Im $\chi(\omega)$ as follows:

$$\mathrm{Im}\,\chi(\omega) \sim \left[1 - \exp\left(-\frac{|\omega|}{T}\right)\right] \mathrm{sgn}\,(\omega)\,. \tag{1}$$

We can immediately see that at two limiting cases for $|\omega| \gg T$ and $|\omega| \ll T$, equation (1) obviously reduces to that assumed in the MFL theory. But $\mathrm{Im}\,\chi(\omega)$ given in Eq. (1) is a continuous function of ω and T, and has no discontinuity at $\omega \sim T$.

In this paper, we will try to use Eq. (1) to elucidate the results from the angle-resolved photoemission spectroscopy (ARPES), which is one of the most important experiments at present in the field of high-T_c superconductors because it can give us the answers to some really basic questions about both the normal state and the superconducting state, e.g., can it be described by a Fermi liquid theory? and what are the characteristics of the gap? The MFL theory predicted that the quasiparticle spectral function $A(k,\omega) \sim |\omega|$ near the Fermi surface and naturally violates the result from the conventional Fermi liquid theory. As will be seen later, according to our model, the above prediction of the MFL theory can be only correct for $|\omega| \gg T$, and near the Fermi surface there should be a narrow region of ω in which the spectral function $A(k,\omega) \sim \omega^2$, which is just the same as that of the conventional Fermi liquid theory.

From Eq. (1), it is easy to get the retarded one-particle self-energy,

$$\mathrm{Im}\,\Sigma(q,\omega) = -c|\omega|[1 - e^{-|\omega|/T}]\,, \quad \mathrm{Re}\,\Sigma(q,\omega) = \frac{2c\omega}{\pi}\ln\frac{x}{\omega_c}\,, \tag{2}$$

where $x = \max(|\omega|, T)$, c is a constant and ω_c is a cut-off frequency. It is well known that the one-particle Green's function can be expressed in terms of the self-energy $\Sigma(q,\omega)$ via Dyson's equation

$$G(k,\omega) = [\omega - \mathcal{E}(k) - \Sigma(k,\omega)]^{-1}\,, \tag{3}$$

where $\mathcal{E}(k)$ represents the single particle energy. The quasiparticle spectrum can be easily obtained from Eq. (3),

$$\begin{aligned} A(k,\omega) &= -\frac{1}{\pi}\,\mathrm{Im}\,G(k,\omega) \\ &= \frac{(c|\omega|/\pi)(1 - e^{-|\omega/T})}{[\omega - \mathcal{E}(k) - (2c\omega/\pi)\ln(x/\omega_c)]^2 + [c|\omega|(1 - e^{-|\omega|/T}]^2}\,. \end{aligned} \tag{4}$$

Selecting an appropriate value of the constant c, and fixing at a temperature T we calculated the spectral functions $A(k,\omega)$ as a function of ω following from Eq. (4) for three different $\mathcal{E}(k)$. The results are shown in Fig. 1, from which the difference of $A(k,\omega)$ from that of the conventional Fermi liquid and the MFL theory are subtle but can be distinguished. The difference may be more easily observed in Fig. 3 which shows an enlarged portion near $\omega = 0$ of the spectral function summed over the wave vector k.

In the angle-resolved photoemission spectrum experiment, one beam of high energy light interacts with a crystal and the electrons in it may be excited by absorbing the photons. If the photon energy is sufficiently high, due to energy conservation the excited electrons will be able to get enough energy to overcome the potential barrier and jump out the crystal. These photoemitted electrons can be detected, and therefore the spectrum for removing one electron from the crystal may be determined by analyzing the energy and momentum distribution of these electrons. Usually, the angle-resolved photoemission spectrum can be expressed by the quasiparticle spectrum $A(k,\omega)$ and the one-particle density of states $N(\omega < 0) \sim \sum_k A(k,\omega)$. In our model performing summation over k for Eq. (4), $N(\omega)$ can be obtained and the result for $T = 0.05$ (in units of ω_c) is shown in Fig. 2, from which we clearly see that 1) very near the Fermi surface, the $N(\omega)$ approaches zero quadratically; 2) with $|\omega|$ further increasing, the

$N(\omega)$ becomes approximately linear variation with ω; 3) the higher energy portion, $|\omega| > 0.3$, of the spectrum shows a constant and rather significant background.

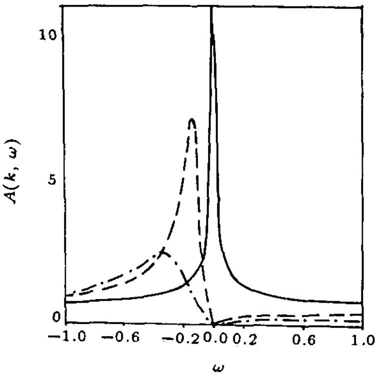

Fig. 1. The spectral function $A(k, \omega)$ at temperature $T = 0.05\omega_c$ for different values of $\mathcal{E}(k)$. Solid line, $\mathcal{E}(k) = 0$; dashed line, $\mathcal{E}(k) = -0.5$; and dot-dashed line, $\mathcal{E}(k) = -1.0$ (in units of $\omega_c, \omega_c = 1200\ \text{cm}^{-1}$).

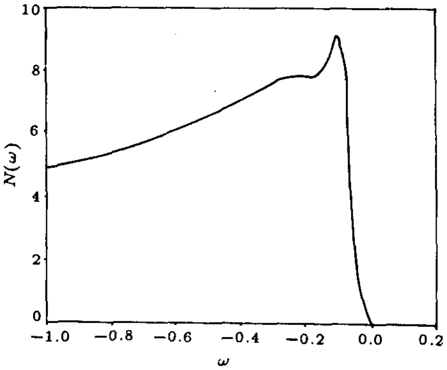

Fig. 2. Calculated density of states $N(\omega)$ vs frequency ω (in units of $\omega_c = 1200\ \text{cm}^{-1}$).

In order to investigate more carefully the first two points said above, we have enlarged the lower energy portion near the Fermi surface, $|\omega| < 0.1$, of the spectrum and shown it in Fig. 3. Also one straight line and one quadratic curve are drawn in the figure for respectively fitting the corresponding portion of the $N(\omega)$ spectrum. The good fitting in both separate regions demonstrates a basic property of our model: near Fermi surface there exists a narrow region of $|\omega| < T$ in which the density of states $N(\omega) \propto \omega^2$, showing the characteristic of a normal Fermi liquid. This conclusion is consistent with those of the highly correlated Fermi liquid model[11], the nested Fermi liquid model[6] and the antiferromagnetic spin-fluctuation model[12] recently proposed, but different from the result of the MFL theory. This prediction of our model has not been approved by the experimental observations at present time, most probably, because the present experimental resolution near the Fermi level is not fine to make it possible to detect this narrow region showing the Fermi liquid behavior. With improving the experimental techniques for high intensity light sources and the resolution precision, however, this prediction will be able to be tested by future fine photoemission experiments. Away from the narrow region further, the $N(\omega)$ becomes varying linearly with ω. This characteristic is the same as the result from the MFL model and also obtained in the three of the highly correlated Fermi liquid model, the nested Fermi liquid model, and the antiferromagnetic spin fluctuation model, and is absent in the normal Fermi liquid theory. But, it is consistent with the angle-resolved photoemission spectrum[13,14]. Although these results from all different theoretical models are the same, but we have to emphasize that they have different bases because both of our model and the MFL model are only phenomenological, and another three models microscopic. Most probably, the fact that our results are consistent with those from some microscopic models demonstrates from another side the correctness of our phenomenological model.

Existence of a broad tail in the high energy portion of Fig. 2, $|\omega| > 0.2$, is another characteristic of our model and the MFL model. It is interesting to note that this phenomenon has not been found in the three microscopic models quoted above. However, this tail is indeed observed in the photoemission experiment[14] and it violates definitely the conventional Fermi liquid theory. It is one of the important non-Fermi liquid features and may be caused by the incoherent excitations in the system. Whether this broad tail or photoemission background in the spectrum is intrinsic property in the density of states is still a controversial question[15]. It will need more experiments to solve the problem.

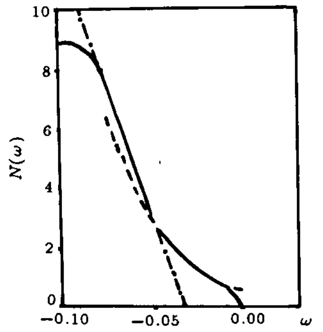

Fig. 3. Same as Fig. 2, but the region near the Fermi level is enlarged. The different portions of the $N(\omega)$ are fitted by the corresponding straight line (dot-dashed), and quadratic curve (dashed).

In conclusion, the angle-resolved photoemission spectrum has been analyzed in this letter by using our phenomenological model proposed previously for the anomalous normal state properties of high-T_c superconductors. The obtained results have also been compared with the MFL theory, other microscopic models, and the experimental observations. Our results demonstrate that the density of states $N(\omega)$ is, in fact, a mixture of the conventional Fermi liquid behavior and the non-Fermi liquid characteristic. We show that the lower energy part of $N(\omega)$ behaves like a normal Fermi liquid, i.e., $N(\omega) \propto \omega^2$, but its higher energy part, on the other hand, behaves like a marginal Fermi liquid, which is consistent with the experimental observations. Our prediction about the lower energy portion of the $N(\omega)$ needs to be tested by more precise experiments in future.

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