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SUPERCONDUCTIVITY

Beware of the pseudogap

In the pseudogap phase of a high-temperature cuprate superconductor, conflicting evidence from different experiments points to a competing state or a precursor-to-superconductivity state. One single experiment now determines that both states exist.

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You probably recognize the situation in which you visit a city for the first time, and you are hosted by someone who enthusiastically describes all the famous places you should definitely see. Occasionally such a place, although famous, is yet inaccessible to the public (10 Downing Street, for example). Upon crossing it from your list, all that remains is a "gap". Your host also warns you to avoid a particular part of town. If safety matters to you, you will follow that advice; however, you may show up in exactly this place if you are inclined to be inquisitive. Such a part of town then constitutes a "pseudogap" in your sightseeing tour. In solid state physics a gap or a pseudogap in the energy bands accessible to electrons near the Fermi-energy is frequently encountered, notably in cuprate high T_c superconductors. Recently Kondo *et al.* witnessed two distinct stages in the evolution of the pseudogap as a function of temperature [1]. According to their interpretation, a pseudogap forms due to strong electron correlation at a relatively high temperature (T^*). At a lower temperature (T_{pair}) they observe an acceleration of its evolution, which they attribute to the formation of uncondensed Cooper-pairs. These pairs ultimately condense at the –still lower- critical temperature (T_c) where the material becomes superconducting.

Sir Nevill Mott introduced the term "pseudogap" in 1968 to indicate a minimum in the density of states [2] at the Fermi energy, $N(E_F)$, resulting from Coulomb repulsion between electrons in the same atom, disorder or a combination of both. Electron-pair formation also results in a pseudogap, irrespective of whether those pairs form a Bose-Einstein condensate or not [3]. All three elements are present in the cuprates. For different stoichiometries, charge carrier concentrations, temperatures and pressure-field conditions in the cuprates, experimental data have been reported demonstrating stripe correlations, anti-ferromagnetism, orbital currents, and pair-correlations, each of which can by itself be held responsible for the pseudogap. Moreover, a (pseudo)gap can open due to strong correlation without symmetry breaking. The pseudogap has been observed in many different types of experiments including Andreev reflection [4], spin-susceptibility [5] optical conductivity [6,7], photo-emission [8] and scanning tunnelling spectroscopy [9]. From a renormalization group analyzes of the Hubbard model near half filling, Honerkamp, Salmhofer, Furukawa and Rice concluded that susceptibilities in different channels (pairing, anti-ferromagnetism) diverge upon tuning the chemical potential [10]. In general a diverging susceptibility provokes instability toward a different state of matter. The presence of several competing near instabilities implies that materials details may tip the balance in favour of one out of several competing phases, each characterized by a (pseudo)gap of different nature. In this regard the rich phase diagram of the cuprates and the large variety of electronic phases reported for these compounds, seem to be natural consequences of aforementioned competing near instabilities.

One difficulty in the cuprates has been the determination of the temperature where the pseudogap opens. If it is due to spontaneous symmetry breaking, it should open at a well-defined critical temperature. If, on the other hand, it is caused by a fluctuation of the superconducting order (similar to a finite fraction of uncondensed Cooper-pairs above T_c), one may expect that increasing the temperature erodes the pairing-amplitude in a rather gradual manner. Kondo *et al.* report the observation of both phenomena in a single experiment: A pseudogap opens upon cooling below a relatively high temperature, which could be the consequence of a spontaneous symmetry breaking. The experiments do not reveal which symmetry is broken. When the temperature is decreased further, a temperature is reached where $N(E_F)$ starts to diminish more rapidly. The authors take this as an indication that a second (pairing) gap begins to open on top of the pseudogap already present. The work of Kondo et al is unique, in that these two temperature scales are revealed in a single experiment.

Experiments such as the Nernst effect [11], which is sensitive to vortices and vortex fluctuations, have shown that the erosion of the pair-correlations as a function of increasing temperature happens rather gradually. For the specific heat this is described by the formula $\ln(T/T_c-1)$ [12]: the only temperature where something abrupt happens is the superconducting critical temperature T_c itself. It is nevertheless possible to *define* a temperature T_c^{mf} (where mf stands for "mean-field") representing the temperature scale for the dissociation of Cooper pairs. Using a method based on entropy balance, Tallon, Storey and Loram estimate that T_c^{mf} is roughly 50% higher than the actual critical temperature [12]. As expected, their specific heat data pass smoothly through T_c^{mf}. This temperature would correspond to T_{pair} in the experiments of Kondo *et al.*, except that these authors conclude that the dissociation of pairs is completed at T_{pair}, as revealed by the surprisingly abrupt change of temperature dependence of $N(E_F)$ at T_{pair}. The results of Kondo *et al.* pose, for this very reason, a novel challenge to experiment and theory alike.

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