Nodes to the grindstone: viewpoint on “Band- and momentum-dependent electron dynamics in superconducting Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ as seen via electronic Raman scattering”

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Materials become superconductors when charge carriers pair up; this pairing is stabilized by an energy gap, the energy cost for creating single-particle excitations. In any new class of superconducting materials, the momentum space structure of this energy gap (or superconducting order parameter) is generally considered to be one of the most important clues to the nature of the pairing mechanism. Determining the order parameter is rarely straightforward, and historically in, e.g. the cuprates, many different types of experiments had to be analyzed and compared before a consensus was achieved. It is therefore not extremely surprising that, nearly two years after the discovery of the high temperature Fe-pnictide superconductors, the symmetry and form of the order parameter in these systems are still controversial. Still, the degree of apparent disagreement among different experiments on similar samples has raised the question: can the superconducting state of these materials be extraordinarily sensitive to either disorder or other aspects of electronic structure which “tune” the pairing interaction?

Based on density functional theory, quantum oscillations and angle-resolved photoemission experiments (ARPES), the Fermi surface of the Fe-pnictides is thought to consist of of a few small hole and electron pockets. Several experiments have been interpreted in terms of order parameters which are isotropic (independent of momentum on a given pocket), but possibly with overall sign change between electron and hole pockets as predicted by theory. On the other hand, many experiments have indicated the existence of low-lying excitations below the apparent gap energy. A natural way of interpreting these observations is to assume that the order parameter has nodes on some part of the Fermi surface, such that quasi-particles can be created at arbitrarily low energies. An alternative explanation for this second set of experiments has been proposed, however; in an isotropic “sign-changing s-wave” (s$_\pm$) superconductor (Fig. 1a), disorder can create subgap states under certain conditions, depending on the ratio of inter- to intraband impurity scattering. From the theoretical standpoint, the most likely states indeed appear to be preferentially of ”s-wave” symmetry, with quasi-isotropic gaps on the hole pockets but potentially highly anisotropic (nodal, e.g. Fig. 1b or near-nodal, Fig. 1d) states on the electron pockets. At present it is not completely clear from these theories what drives the anisotropy on the electron pockets, although some useful observations have been made. It is clearly extremely important to establish empirically whether low-energy excitations are intrinsic (nodal) or extrinsic (disorder-induced), and under what circumstances fully developed gaps should be expected.

In this regard, electronic Raman scattering in the superconducting state is an ideal probe. In addition to sensitivity to low-lying excitations, Raman scattering can be performed for various polarizations of the incoming and outgoing photons, so as to preferentially sample the excitations created in different parts of the Brillouin zone. In a recent article, Muschler et al. have presented Raman scattering measurements on single crystals of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ for two different (near optimal and slightly overdoped) concentrations of Co. Similar measurements and theoretical interpretations were instrumental early on in identifying d-wave pairing in the cuprates, but the scattering from charge excitations is up to an order of magnitude smaller in the Fe-pnictide systems, so the mere observation of a change in the signal with temperature below $T_c$ by Hackl and co-workers is a significant achievement; it indicates that Raman experiments can again play an important role in determining the symmetry of the new materials.

Muschler et al argue that the polarization dependence is crucial to identifying gap structures on different Fermi surface pockets. As the temperature is lowered below $T_c$, one expects the gap in the electronic spectrum to begin to influence the scattering, provided the polarization states are sensitive to the states being gapped. The $A_{1g}$ configuration samples the entire Brillouin zone, but the contributions from the electron pockets are strongly diminished by screening effects; therefore this polarization is primarily sensitive to the hole pockets. The major change with temperature in this channel occurs near 100 cm$^{-1}$, which the authors identify with twice the hole pocket maximum gap $\Delta_{max}$. On the other hand, the data do not appear to be good enough at low energies to allow statements about subgap excitations to be made on these pockets.

In the $B_{1g}$ polarization, the predominant weight factors occur in portions of the Brillouin zone near the X points where, from the point of view of electronic structure calculations, it seems unlikely that Fermi surface crossings exist for an electron doped system. Thus the lack of temperature dependence observed, with the exception of a prominent phonon peak, is understandable.

By contrast only the electron pockets are sampled in the $B_{2g}$ polarization; here a much stronger temperature change is observed as one enters the superconducting
state, with a significant peak near 70 cm$^{-1}$, implying a $\Delta_{\text{max}}$ of about 35 cm$^{-1}$ on these pockets. Note that these gaps are quite close to those determined by ARPES measurements on a Ba-122 sample doped with 7% Co\textsuperscript{4}. In addition, there is a clear low-$\omega$ power law in energy close to $\omega^{1/2}$ visible in the low-temperature data for the optimal Co concentration sample. This is the power law in the density of states one expects for an order parameter on the electron pockets which barely touches the Fermi surface (“kissing state”, see Fig. 1c). It is not consistent with a generic impurity band in an isotropic $s_{\pm}$ state. While the existence of nodes in the $s$-wave channel is “accidental”, meaning it is determined by details of the pairing interaction rather than by symmetry, theoretical calculations have indeed found that the order parameter on the electron pockets comes quite close to “kissing” the Fermi surface\textsuperscript{5}, or slightly overlapping (Fig. 1b-d), and thermal conductivity experiments on the same material\textsuperscript{10} have also been interpreted as implying near-“kissing” states\textsuperscript{11}. Addition of a small amount of Co was found by Muschler et al. to lead to a small range of energies where no excitations were visible, i.e. a small gap of order 10 cm$^{-1}$. Were the effect of the additional Co simply to add disorder to the system, this result would be consistent with the suggestion by Mishra et al.\textsuperscript{9} that intraband disorder scattering has a tendency to average an extended $s$-wave gap with accidental nodes so as to eventually “lift” the nodes and create a full spectral gap. Some evidence for the disorder interpretation is provided by the fact that the $B_{2g}$ peak is considerably broader in the higher Co concentration sample. However, more work needs to be done to rule out a direct effect of the Co on the pair interaction itself via doping or local structural modulations.

Why is the temperature dependence so much more significant on the electron pockets? At the transition, the hole pocket scattering rate–given roughly by the position of the maximum in the Raman intensity–appears to be many times the critical temperature for the hole pockets. On the other hand, the analogous peak appears to occur at an energy of order about 20 cm$^{-1}$ on the electron pockets. Why the normal state lifetimes of electrons should be so much longer than those of holes is not currently understood, but this result appears to be consistent with transport\textsuperscript{13} measurements. The ability to observe sharp transitions at low temperature in the $B_{2g}$ channel implies further that the electron pocket relaxation rate must be even smaller at low temperatures; this is consistent with the collapse of the relaxation rate as the gap opens, as observed in thermal conductivity measurements\textsuperscript{12}. The Muschler et al work provides internally consistent evidence for order parameter nodes on the electron pockets, and for a strong scattering rate anisotropy, largest on the hole pockets in near-optimally Co doped Ba-122. This underlines the question of why many other experiments appear to observe fully gapped states. One possibility is that changes in electronic structure create more isotropic pairing states. It appears likely that the electronic structure of these materials can be quite sensitive to materials parameters, and that relatively small changes can rapidly tune the “accidental” nodes away. The exact nature of this sensitivity will be interesting to try to sort out in the future. Even if this view is correct, however, there is mounting evidence that ARPES measures isotropic gaps even if the bulk states probed by other experiments indicate nodes, implying a possible

![Figure 1: Schematic representations of possible $A_{1g}$ type states discussed by Muschler et al. Top panel: order parameter plotted as function of local angle circling the hole ($\alpha$) and electron ($\beta$) pockets. Dashed line represents $\Delta = 0$. Bottom panel: corresponding density of states for clean system. a) Isotropic $s_{\pm}$ state; b) Anisotropic $s$-state with nodes on $\beta$ pockets; c) Same as b) but for state with marginal (“kissing”) nodes; d) Same as b) but for deep gap minima.](image-url)
strong dependence of this pairing state on surface conditions as well. As in previous attempts to determine order parameter symmetry in new superconducting materials, only by comparing different experiments on high quality samples of various materials may one expect a consensus to emerge.

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