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Concluding Remarks: Experiment from a materials perspective

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Abstract. The author provides some remarks regarding the current status of experiments in strongly correlated electron systems. By construction, they are biased by the author's perspectives at the time of writing.

Characterization techniques have progressed enormously since the early studies of strongly correlated electron materials, along with ever increasing sample quality and the present dominance of single crystal work in our field. Scanning tunneling microscopy that is just beginning to be turned to the study of cleaved surfaces of heavy Fermion materials and should be able to provide detailed information at the atomic level that we have never had before. Correlated electronic structure is expected to be particularly labile in the vicinity of a surface and interpreting exactly how STM measurements reflect the bulk physics will be interesting to sort out. Using the STM as an experimental knob presents interesting possibilities as well, such as locally inducing superconductivity. Ever increasing sensitivity in photo-emission experiments now approaches the energy scales of direct electronic interest. Further, the new combination of various techniques, for example neutron scattering plus x-ray absorption as presented by Severing, can further address the low temperature electronic structure in remarkable detail at the local level.

Much of the physics of interest in heavy Fermion materials occurs near a magnetic quantum critical point. Connected with this is the observation that certain physics, such as the nematic phase suggested in $Sr_3Ru_2O_7$, depends sensitively on the perfection of the material. This points to the need to characterize materials thoroughly via x-ray and related techniques. Modern light sources enable x-ray experiments never before possible: modern x-ray technique can provide structural detail that can deepen significantly our understanding of the physics and chemistry of strongly correlated electron materials.

Superconductivity has been in a certain sense the black hole organizing the galaxy of correlated electron materials. The idea that the magnetic fluctuation spectrum in dense Kondo liquids can support both antiferromagnetism and superconductivity appears consistent with the apparent general occurrence of heavy Fermion superconductivity near a magnetic quantum critical point. It is not so clear in this regard that actinide materials map exactly onto the Ce materials or why Yb heavy electron materials so far have only shown one instance of superconductivity. Why $PuCoGa_5$, which would seem to be naturally classed with the other 115 superconductors, has such a highT_c remains a mystery. A related question is whether the 2.3K maximum T_c observed so far for Ce heavy Fermion

superconductors might be some kind of natural limit for Ce heavy Fermions and whether some kind of local atomic physics plays significantly into correlated electron superconductivity.

The large amount of Fermi surface data that is now available for highly correlated electron materials provides important input for assessing how well the increasingly sophisticated electronic structure calculations are doing in coming to grips with electronic correlations. But what deeper lessons can we take from our knowledge of the Fermi surface? We can understand magnetic instabilities in terms of Fermi surface features but the same cannot be said for superconductivity. For example, superconductivity occurs in $CeRhIn_5$ at pressures below where its Fermi surface changes into one closely resembling that of $CeCoIn_5$. Coupling this with the observation that highly correlated electron superconductivity appears to favor certain crystal structures suggests that superconductivity might really be a chemistry problem.

The discovery of new materials continues to surprise. Superconductivity coming to terms with magnetism has been and is still a driving force in the field, and this acquires new forms. Heavy Fermion superconductivity has many aspects that bear directly on the physics of high T_c. The many faces of frustration are seen throughout correlated electron physics. Quantum criticality itself presents a type of frustration. Behind all new materials work is the motivation to understand structure/property relationships. What kind of progress does one make here? In detail, not much. In the more general sweep of 4f to 5f to transition metal compounds we might hope some patterns to emerge, but this progress is slow. The cleanest case of correspondence across this progression is with the Kondo insulator materials and perhaps this route might be generalized. These materials are a version of valence, or electron precise, compounds.

What else is interesting about intermetallics which appear to obey valence rules? We are usually dealing with semimetals, and it is interesting to note that one extreme of the cuprate and the iron pnictide materials are of this sort. At this extreme, for example with La_2CuO_4, one has a layered structure with significant charge separation between layers: the bonding differs between inter- and intra-layer. The layers appear as entities in themselves, stabilized by their 3D arrangement. Such a picture gains legitimacy from the computations described by Grin. A lot of interesting things happen when conduction electrons are present, either from band overlap or deliberate doping. In a loose way from this vantage point, we might ask what is it about URu_2Si_2 that makes it act so strangely? Perhaps we can regards RuSi as $(RuSi)^{-2}$, so that $U^{+4}(RuSi)^{-2}{}_2$ is actually a low carrier density system with some similarity to the 122 pnictides. The more general point is that there is use to not only exploring what is happening, but also why it happens in one instance and not in another.

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