Collective mode of Magnetization in Heavy Fermi Liquids

Evolution of the Kondo state of $YbRh_2Si_2$ probed by high field ESR
Authors: U. Schaufuß, V. Kataev, A. A. Zvyagin, B. Büchner, J. Sichelschmidt, J. Wykhoff, C. Krellner, C. Geibel, and F. Steglich.
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Electron spin resonance in Kondo systems
Authors: Elihu Abrahams and Peter Wölfle,
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Recommended with a Commentary by Chandra Varma, University of California, Riverside

Heavy-Fermi liquids with renormalization parameters often as large as $O(10^3)$ show just how wide the limits of applicabiity of the ideas of analyticity and continuity underlying the Landau theory of Fermi-liquids can be. This has been known for many years for the low temperature thermo-dynamic and transport properties of many rare-earth and actinide compounds, which at low enough temperatures have temperature dependences of the Sommerfeld theory of free-fermions but with colossal renormalizations in some properties and essentially none in some others, as dictated by conservation laws. The first paper above and its antecedents have discovered Conduction Electron Spin-Resonance (CESR) in an interesting heavy-fermion compound, URS for short. CESR is really the collective mode of Magnetization, $\mathbf{M}(\mathbf{q}, \omega)$ for $q \to 0$, in an external magnetic field H, which is expected in a Fermi-liquid in the condition that the spin-diffusion time is long compared to the resonance frequency. The experiments are done across the crossover region in the magnetic-field - temperature (H-T) phase diagram due to a mysterious quantum-critical point, where the properties change from that of a Fermi-liquid to a non-Fermi-liquid displaying singularities in the low energy/temperature correlations. A quick look at the experiments in the Fermi-liquid region would hardly tell the difference of the results from that in metallic Na or K, which have hardly any observable renormalizations from electron-electron interactions. In the non-Fermi-liquid, where the crutch of Landau theory is missing, interesting new questions arise.

These matters are analyzed in the second paper and another in preparation by the same authors containing more detailed comparison with experiments. They tend to dispel some earlier confusion in understanding what is essentially a macroscopic effect, through improperly mixing it with the microscopic underpinnings of the renormalizations (Kondo effect) in heavy fermi-liquids. The literal interpretation of parameters in the theory paper might in turn also lead to some misunderstandings.

The CESR is the resonance in the transverse spin-susceptibility; this can be complicated in general but it is enough for the present purposes to represent it by a function with a simple pole off the real axis:

$$\chi^{+-} \approx \frac{\chi_{0,\hat{\mathbf{H}}}}{\omega - \omega_0(H,T) - i\Gamma(H,T)}. \quad (1)$$

$\chi_{0,\hat{\mathbf{H}}}$ is the uniform magnetic susceptibility in the direction of $\mathbf{H}$.

The principal experimental discoveries are:
(1) There is a well-defined resonance in URS (a tetragonal crystal) with a renormalization in ω_0 or of the g-factor of ≈ 3.6 and moderate width Γ with field along the c-axis but not with field in the plane, (2) g is temperature independent in the fermi-liquid regime and $\Gamma \propto T^2$, the quasiparticle relaxation rate; their renormalization would not suggest that there is any large renormalization of $O(10^2)$ as in specific heat and magnetic susceptibility. Since $\chi_{0,\hat{\mathbf{H}}}$ has an order of magnitude anisotropy, the visibility of the resonance with $\mathbf{H}$ parallel to the c-axis and its invisibility with field in the plane is not surprising. The interesting questions have to do with the renormalizations in ω_0 and Γ with T, H due to the interactions. (3) ω_0 and Γ acquire a temperature dependence when there is a crossover into the non-fermi-liquid regime which reflect the singularities in other properties.

The first theory of the conduction electron spin-resonance, in non-interacting electrons, is due to Dyson in the 1950's. Since the interacting Hamiltonian commutes with the spin operators in the limit of zero spin-orbit interactions, the resonance frequency is unaffected by the interactions and its width is zero in the limit of $T \to 0$. With spin-orbit scattering, the interactions change the frequency but the g-factor or ω_0 is renormalized only by the Landau parameter $(1 + F_0^a)$, which gives the ratio of the magnetic susceptibility renormalization to the specific heat renormalization. The total magnetic susceptibility renormalization only enters in to the amplitude χ_0. The proportionality of the line-width to T^2 reflects the line-width of the incoherent quasi-particle magnetization into which the spin-resonance decays, it is similar to the temperature dependence of the resistivity in a similar region measured in the compound; both show large renormalizations (while the residual resistivity due to impurities does not.)

The paper by Abrahams and Wölfle (A-W) uses the model of two species of hybridized-fermions with which the heavy-fermion lattice has often been studied. The physical basis of such a model is the phase-shift of $\pi/2$ of conduction electrons at the chemical potential scattering off a Kondo impurity (the f-electrons) which if implemented for a periodic array of f-electrons gives hybridized bands. The width of the Kondo resonance enters the hybridization parameters of the model. At this level the theory is equivalent to a microscopic theory with an on-shell momentum-independent self-energy. This approximation leads to a Fermi-liquid with Landau parameters quite different from that, say for Liquid He^3 but which predicts renormalizations in various properties which are well satisfied in experiments. (Another crucial difference of heavy-fermi-liquid renormalization from He^3 comes from the inapplicability of Galilean invariance in a two-component system with different one-particle and interaction parameters.) For ESR, $(1 + F_0^a)$-type renormalization and spin-orbit scattering (already incorporated in the one-particle properties of the model) are needed which are treated in a RPA-like manner with additional parameters. It is of-course well-understood by the authors that one does not know what these parameters really mean. But sensible qualitative answers in terms of the assumed model are given because RPA respects conservation laws. The Landau transport equation itself has the structure of RPA with renormalized parameters whose meaning is known in simple cases (like He^3), but which are impossibly hard to calculate for strongly interacting problems. It might be worthwhile to write down a Landau-transport equation in a two-component system of fermions and interpret result in terms of Landau parameters for heavy -fermions. The two-component nature would require introducing some new features.

In the singular or non-fermi-liquid regime, the experiments show that the ω_0 acquires a logarithmic temperature dependence, just like for example the specific heat and Γ acquires a linear temperature dependence, just like the resistivity. As far as I know the magnetic susceptibility does not have a log-T dependence. I find it very interesting that ω_0 acquires the singularity evident in the specific heat in this regime, while its large constant renormalization cancels out. This is deserving of further experiments. These are hard to carry out in the critical regime for URS and may be better carried out in other compounds.