Review of typical behaviours observed in strongly correlated systems

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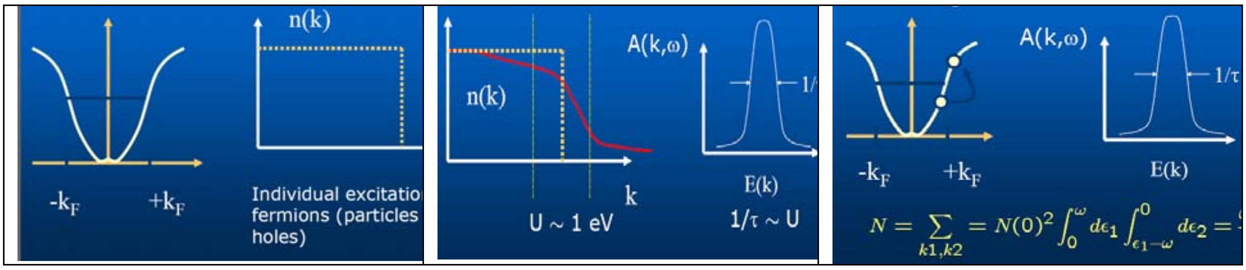
Introduction :

Major part of solid state physics of the second part of the 20th century was based on industry of semiconductors, based itself on the “physics of a single electron”. This concept is based on the “effective carrier approximation”, in which each electron is assumed to be independent from the others, free electron or quasi free electron with an effective mass and a life time which includes the whole physics of the interactions. Nowadays, strongly correlated systems are extensively studied: superconductors, magnetic materials, “heavy fermions” and other metal-insulator transition systems. These phenomena are observed in many applicative materials such as thermoelectricity, transparent conductors, magnetic memories and captors, superconductors, etc…

In this lecture, a brief review will be presented.

Fermi liquid approximation

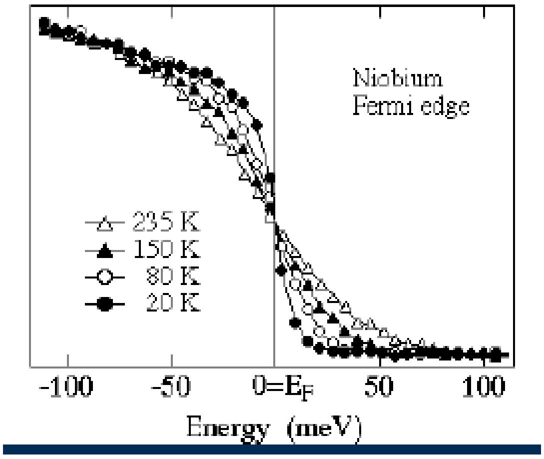
The Fermi liquid approximation is well understood.

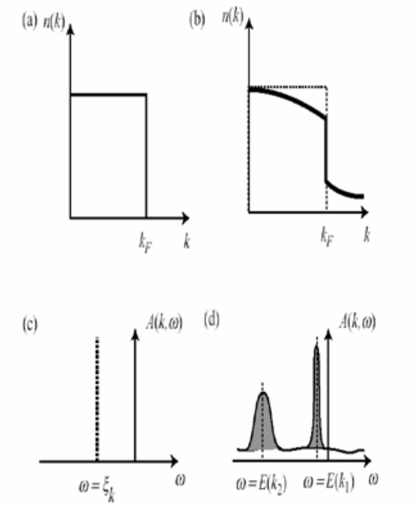


The effect of the coulomb repulsion (from T. Giamarchi): in absence of repulsion (left), in presence of repulsion (1eV) (middle), with screened repulsion (Fermi liquid) (right).

Excitations are individual excitations labelled in the reciprocal space in k. At zero temperature, the “electrons” are occupied up to the Fermi energy. To calculate non zero temperature properties, one performs a “Sommerfeld expansion” which provides the specific heat C_p linear in T and a life time of the carriers in $1/\omega^2$. Despite the fact that it looks crazy (Coulomb repulsion U is about 1eV, to be compared to the temperature 25mEV at 300K), the screening of the repulsion is very efficient. This gives a resistivity in T^2.

Photoemission is a good method to study the response function, despite a lot of technical difficulties (surface effects, empty states convolution, …).





Heavy fermions

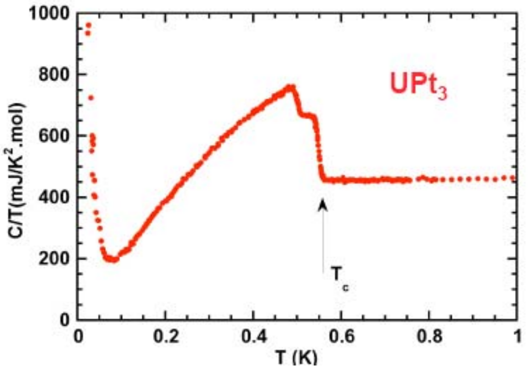
In some materials, such as UPt3, the effective mass m, determined by specific heat measurement can reach 1000 times that of copper.

- Macroscopic manifestations:

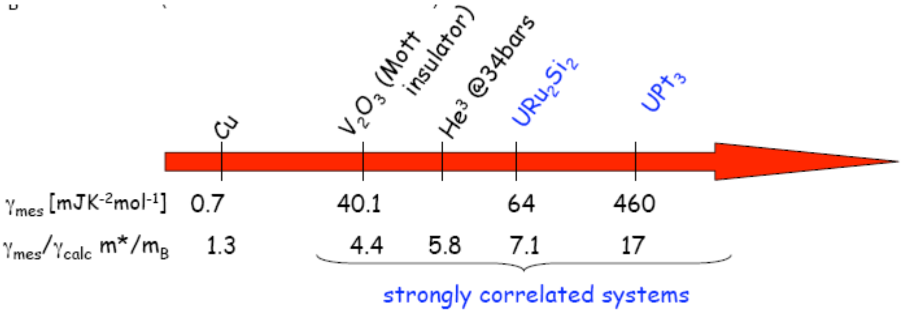
  large Sommerfeld coefficient
  (Cu : γ~0.5mJ/K²·mol)

$$C_v \approx nk_B \frac{k_B T}{E_F} \Rightarrow \gamma \approx nk_B^2 \frac{m^*}{(\hbar k_F)^2}$$

γ-UPt$_3$ ~1000 γ-Cu (/mol)



Fermi velocity is 4700m/s, 300 times smaller than copper (deHaas-vanAlphen effect).



The ratio m* over band mass is the important parameter. The physical origin is the electron-electron coupling. Such compounds can be found in actinides (5f) or rare-earth(4f) intermetallics:

$CeAl_3$, $CeCu_6$, $CeCu_2Si_2$, $CeCoIn_5$… but also $PrOs_4Sb_{12}$, UPt_3, … The origin is the magnetic moment:

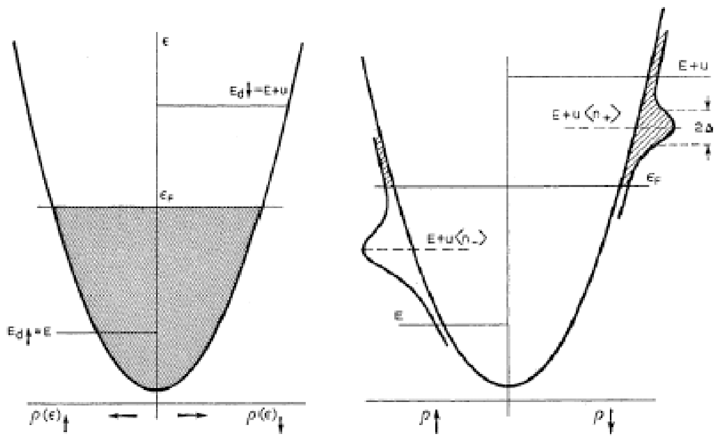
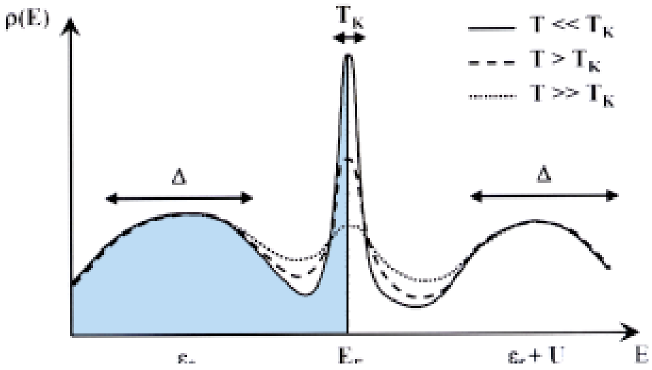


FIG. 1. Unperturbed energy levels in the absence of s-d admixture.

The ferromagnetic exchange is $J=t^2/U$, where t is the coupling and U the repulsion energy.

The important model is the Kondo model with a Kondo temperature T_k. (A single magnetic impurity in a metal).

The effective mass is T_F/T_K.



Magnetism

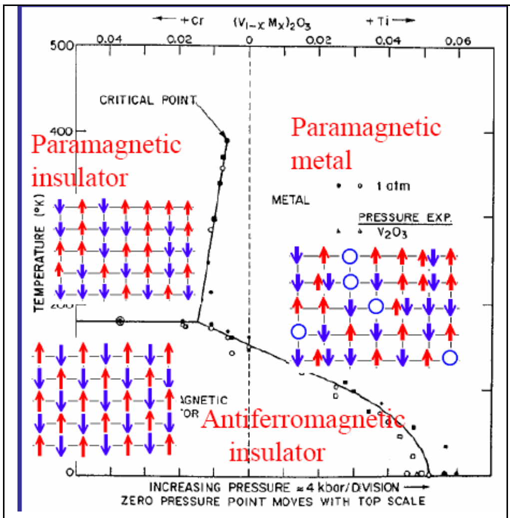
In such systems, there is the possibility of ferromagnetic or antiferromagnetic states, due to this exchange term ($J=t^2/U$).

Low dimensional effects

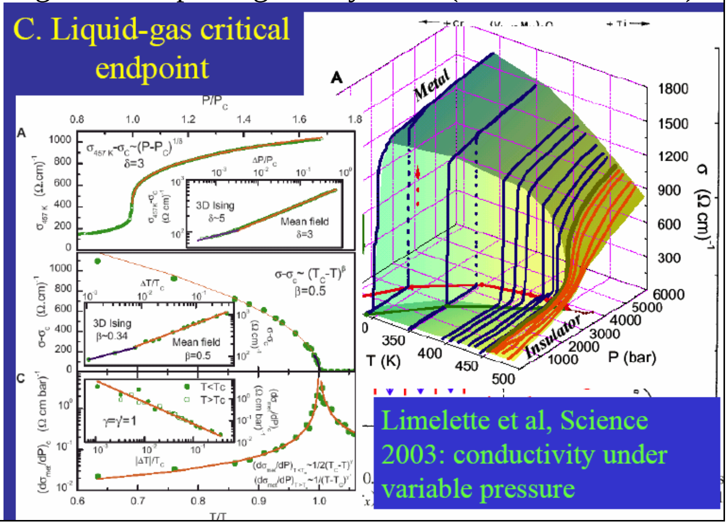
In low dimensions, there are specific effects such as nesting of the Fermi surface which modifies the properties. There is a spin charge separation and a special electron state (Luttinger liquid) where the transport properties are different. There are no fermionic quasiparticules (no individual excitations), but charge density waves and spin density waves. There is also the possibility of fractional charge excitations.

Insulator-metal transition, Mott insulator.

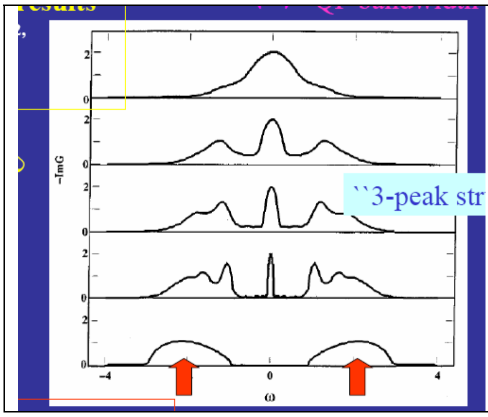
Due to competition between coulomb repulsion U and kinetic energy t, it appears a insulating-metal transition from Mott insulator to Fermi metal. This transition is similar to liquid-gas transition. In V_2O_3, pressure can vary the parameter t.



A good example is given by V_2O_3 (P. Limelette et al.)



A computation method, named DMFT (Dynamical mean field theory) allows to compute simple models and explain these properties.



This figure is a typical result obtained by DMFT for increasing U/t from top to bottom. The surprising feature is the narrow peak in the intermediate state which corresponds to carriers with a high effective mass. This is a the origin of a lot of spectacular properties such as high thermopower of cobaltites.

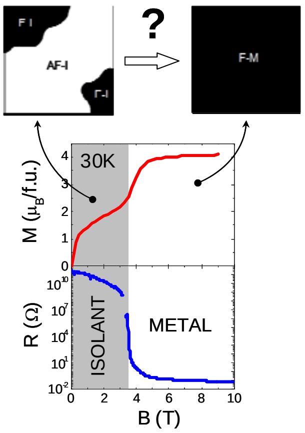
Superconductivity

Superconductivity is also a possible state of strongly correlated fermions. It corresponds to the pairing of two electrons to create bosons which have the possibility to condensate in a superconducting state. Resistivity is zero, and magnetism is fully diamagnetic. Specific heat is gapped, as well as excitations. This is also a very rich domain that we don't have time to investigate here. In mercury, lead or niobium, the origin of the coupling is electron phonons, but this is not general. In particular in cuprates, the origin is not really understood.

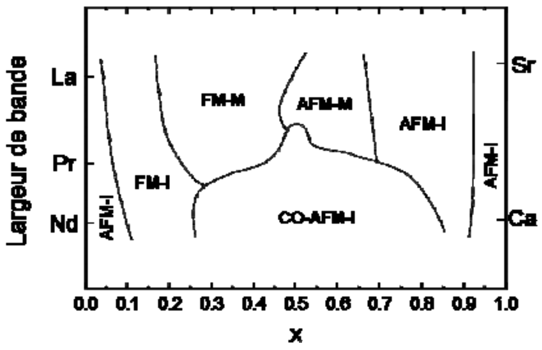
Conclusion

The physics of strongly correlated fermions is very rich, with a lot of possible applications. But it is also quite complex, with number of unsolved problems…

A typical example is that of manganites, in which there are at the same time, strongly correlated electrons, coupling with the phonons, Jahn-Teller effect and disorder effects which drive to very complex phase diagrams and various properties such as colossal magneto resistive properties due to electronic phase separation and percolation between two phases.



The colossal magnetoresistance at the percolative transition for x=0.3.



Typical phase diagram of $Pr_{1-x}Ca_xMnO_3$

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