Pomeranchuk effect in unstable Ytterbium systems

Mucio A. Continentino and André S. Ferreira
Instituto de Física, Universidade Federal Fluminense,
Campus da Praia Vermelha,
Niterói, RJ, 24.210-340, Brazil

(Dated: November 21, 2018)

YbInCu$_4$ and its alloys present discontinuous, first order iso-structural transitions at pressure dependent temperatures $T_V(P)$, where a local moment phase coexist with a renormalized Fermi liquid phase. We show that along the coexistence line $T_V(P)$ the entropy of the large volume renormalized Fermi liquid phase is smaller than that of the higher density, local moment phase. This implies the existence of a Pomeranchuk effect in these Kondo lattice materials in analogy with $^3$He. The theoretical possibility of using these systems as cooling machines is discussed.

PACS numbers: 71.28.+d; 71.27.+a; 65.50.+m; 64.10.+h

The system $^3$He presents the unusual feature that along its melting line, where the solid and liquid phases coexist, the entropy of the liquid is smaller than that of the solid. This occurs for a range of temperature $T < T_X = 0.32$K, where the melting pressure versus temperature curve has a minimum, but for $T > T_X$, the temperature of magnetic ordering of the solid. This feature is the basis of the cooling technique known as the Pomeranchuk effect, which had an important practical application as a cooling mechanism to reach very low temperatures in this system. It is believed to be a unique property of quantum $^3$He and is a direct consequence that in its liquid phase this is a renormalized Fermi liquid, with a linear temperature dependent entropy ($S_L/Nk_B = 3.0T$) while in the solid phase for the temperature range above, it may be seen as a collection of weakly interacting spin-1/2 local moments with $S_S/Nk_B \approx \ln 2$. Also for the low temperatures associated with this behavior of $^3$He, elastic excitations (the phonons) are quenched and the relevant degrees of freedom are the magnetic ones due the spin-1/2 nuclei.

The Kondo lattice system YbInCu$_4$ presents isostructural transitions, which for the pure system at ambient pressure ($P \approx 1$ bar) occurs at a temperature $T_V = 42$K. This is a discontinuous, first order transition which is accompanied by large changes in transport properties and in magnetic behavior. In Fig. 1 we show the temperature dependent magnetic susceptibility of YbInCu$_4$ in the range of the isostructural transition. Above $T_V$, the susceptibility is of the Curie-Weiss type characteristic of a system of weakly interacting local moments ($\Theta \approx -7.2$ K). Below the transition, the susceptibility is nearly temperature independent, i.e., Pauli like as in a Fermi liquid. The value of $\chi_0$ indicates a renormalized value consistent with the coefficient of the linear term in the specific heat, $\gamma = 50$ mJ/molK$^2$. This leads us to consider YbInCu$_4$ in its low temperature phase as a moderate heavy fermion system.

This picture of YbInCu$_4$ at $T_V$ as a renormalized Fermi liquid phase coexisting with a local moment phase at a line of first order transitions $T_V(P)$ brings out a powerful analogy with $^3$He.

FIG. 1: Susceptibility curve for YbInCu$_4$ (schematic). At $T_V \approx 42$K ($P \approx 0$) there is a discontinuous, first order isostructural transition with a volume increase in the low temperature phase. At $T_V$ a local moment phase coexists with a renormalized Fermi liquid phase.

Along the melting line $T_m(P)$ of $^3$He and the line $T_V(P)$ of the present system, we find coexistence of a renormalized Fermi liquid phase and a phase of local moments (in $^3$He the liquid and solid phases, respectively).

The nature of the coexisting phases in YbInCu$_4$ leads us to expect that as in $^3$He, the Fermi liquid phase of this material has a smaller entropy that of the local moment phase for some range of temperatures where these phases coexist.

The Clausius-Clapeyron equation, as applied to the YbInCu$_4$ system can be written as,

$$\left( \frac{dP}{dT} \right)_{T_V(P)} = \frac{S_{FL} - S_{LM}}{V_{FL} - V_{LM}}$$

where the derivative is obtained at the volume instability curve $T_V(P)$. The entropy of the local moment phase and of the renormalized Fermi liquid phase are given by $S_{LM}$ and $S_{FL}$, respectively. Notice that, since both phases are truly solid and the change in volume is small (see Table 1), the difference ($S_{FL} - S_{LM}$) is mostly due to the magnetic degrees of freedom. In $^3$He the derivative
in Eq. I is calculated at the melting curve where the solid and liquid coexist. In this system, the melting pressure as a function of temperature passes through a minimum at $T_x$, where $S_{\text{solid}} = S_{\text{liquid}}$ and presents a negative $(dP/dT)$ for $T < T_x$, consistent with $S_{\text{solid}} > S_{\text{liquid}}$ in this range, since the molar volume of the liquid $V_L$ is larger than that of the solid, $V_S$.

A plot of the instability temperature for $YbInCu_4$ as a function of pressure $T_V(P)$ (or $P(T_V)$), obtained from resistivity measurements is shown in Fig. 2. From the Clausius-Clapeyron equation, the experimental negative sign of $(dP/dT)$ at $T_V$ and the fact that the molar volume in the Fermi liquid phase of $YbInCu_4 (V_{FL})$ is larger than that of the local moment phase $V_{LM}$, we can conclude that the entropy of the former ($S_{FL}$) at the coexistence line $P(T_V)$ is smaller than that of the local moment phase, for this range of temperatures, just as in $^3He$ for $T < T_x$. As pointed out before, the features $S_{FL} < S_{LM}$, $V_{FL} > V_{LM}$ are at the root of the Pomeranchuk effect in $^3He$ which, as we have just shown, also occurs in the Kondo lattice system $YbInCu_4$.

In Table I we list for comparison some thermodynamic parameters of $YbInCu_4$ and $^3He$. Notice that for the former material, $(T_x, P_x)$ are obtained from a crude extrapolation of the Fermi liquid entropy $S_{FL}/Nk_B = 6.0 \times 10^{-3}T$ up to that of independent local moments $S_{LM}/Nk_B = \ln(2J + 1) = \ln 8$.

In the case of $^3He$ the Pomeranchuk effect is the basis for the construction of a practical apparatus which has provided the means for attaining very low temperatures in this system and eventually discovering its superfluid phases. The results above show the theoretical possibility of constructing a Pomeranchuk cooling machine based on the Kondo lattice system $YbInCu_4$. An estimation of the cooling efficiency of such machine is given by the ratio $(W/Q)$, where $W = P_V(V_{FL} - V_{LM})$ is the compressional work to squeeze the Fermi liquid into the local moment phase. The quantity $Q = T(S_{LM} - S_{FL})$ is the latent heat which represents the maximum amount of heat which can be converted by the Fermi liquid into the local moment phase. The ratio $W/Q = -(P_V/T)(dP/dT)^{-1}$ attains for $^3He$ its lowest value, $(W/Q) = 13$, at $T = 0.14K$. For $YbInCu_4$ this can be much smaller, for example, $(W/Q) = 0.08$ at $T = 40K$ using the value of $(dP/dT)$ obtained from Fig. 2 (see Table I).

![Fig. 2: Pressure of the volume instabilities in YbInCu4 as a function of temperature, obtained from resistivity measurements.](image)

![Table I: Thermodynamic parameters for $^3He$. Ref. and YbInCu4, Ref. for YbInCu4 were obtained extrapolating the Fermi liquid entropy to reach to non-interacting local moment value.](table)

![Fig. 3: Schematic temperature variation of the entropy of the Fermi liquid and local moment phases at the instability field $H_V$. Cooling can be achieved by isentropically increasing the magnetic field to bring the FL phase into the LM phase as in a process from $A$ to $B$.](image)
be used as the *compressing agent* which is simpler than actually squeezing the Fermi liquid.

In this Letter we have shown the existence of a Pomeranchuk effect in $YbInCu_4$ and its alloys, which opens the theoretical possibility of using these materials as cooling machines. Our approach suggests to view the transition at $T_V$ in $YbInCu_4$ as the melting of a Kondo lattice.

Acknowledgments

We would like to thank Conselho Nacional de Desenvolvimento Científico e Tecnológico-CNPq-Brasil (PRONEX/98/MCT-CNPq-0364.00/00), Fundação de Amparo a Pesquisa do Estado do Rio de Janeiro-FAPERJ for partial financial support. We thank J. C. Fernandes and E. Miranda for useful suggestions and discussions.

* Electronic address: mucio@if.uff.br

1. I. Pomeranchuk, Zh. Eksp. i Teor. Fiz. (USSR) 20, 919 (1950); R. C. Richardson, Rev. Mod. Phys. 69, 683 (1997).
2. D. S. Betts, *Refrigeration and Thermometry below One Kelvin*, Sussex University Press, 1976.
3. I. Felner and I. Nowik, Phys. Rev. B33, 617 (1986).
4. J. L. Sarrao, Physica B259-261, 128 (1999) and references therein.
5. M.O. Dzero, L.P. Gorkov and A.K. Zvezdin, J.Phys.-Cond.Mat. 12, L711 (2000).