Thermoelectric Effects in S-N-S Weak Links with Heavy
Fermions as The Normal Metal: A Possibility for Thermosensors

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Abstract

It is shown that S-N-S weak links with an heavy-fermion metal as the weak
link (N) can be useful thermosensors. This property is due to the large ther-
mopower of heavy-fermion metals which is of the order $10^{-6} \, V/K$. The longi-
tudinal sound can also generate voltage oscillation due to the large Grüneisen
parameter, $\Omega_{hf} \sim 10^2$, in heavy-fermions. Similar effects are expected with
other Kondo systems as the weak link.
I. INTRODUCTION

It is well known, that below some characteristic temperature $T^*(\approx 20 - 100 \text{ K})$ heavy-fermion (HF) metals, which contain magnetic ions with 4f or 5f electrons, are characterized by the large quasiparticle mass $m_{hf}$. The latter is several hundred times larger than the electron mass $m_e$ - see for instance[1], and these systems are strongly renormalized Fermi liquids below $T^*$. As a consequence, various thermodynamic and transport properties are significantly renormalized below $T^*$. For instance, there is a significant increase: (1) in the low temperature specific heat ($C_p = \gamma_{hf} T$), where $\gamma_{hf} \sim 10^3 \gamma$ with the typical value for alkali metals $\gamma \sim 1 mJ \text{ mol}^{-1} K^{-2}$; (2) in the spin paramagnetic susceptibility; (3) in the electronic Grüneisen parameter $\Omega_{hf} = -d \ln T^* / du$ ($u$ is the strain field), where for instance $\Omega_{hf}$ of the HF metal $UPt_3$ is 100 times larger than in standard alkali metals; (4) in the thermoelectric power $Q_{hf} \sim 10^2 Q$ where $Q$ is the value for the standard alkali metals. The main reason for this renormalization is the presence of the Abrikosov-Suhl-Kondo (ASK) resonance in the quasiparticle density of states at the Fermi level. The latter is due to the Kondo effect in the lattice of 4f (or 5f) magnetic ions - for more details see[1,2].

The large longitudinal sound absorption measured[3] in $UPt_3$ around $T \approx 10 \text{ K}$ is explained in Ref.[4] by the large values of $\Omega_{hf}$ and $Q_{hf}$, which cause large temperature fluctuations during sound propagation. Note that in standard alkali metals (which are weakly renormalized Fermi liquids) the effect of temperature fluctuations on the sound absorption is negligible. In Ref.[5] it was proposed a setup which might prove the existence of thermoelectric effects in superconductors. It is also based on the large value of the thermopower

$$Q_{hf} \approx -\frac{3T}{|e| T^*}$$  \hspace{1cm} (1)

in the normal state of the HF metal $UPt_3$ (and also in the superconducting state near $T_c < 1 \text{ K}$). It is worth mentioning that in $UPt_3$ the characteristic value is $|Q_{hf}| \sim 10^{-6} T \text{ V/K}$, where $T$ is measured in $K$. If the HF superconductor with large $|Q_{hf}|$ is part of a ring with two metallic contacts at different temperatures such a system gives rise to a large
induced magnetic flux $\Delta \Phi$ inside the hole of the ring. In the ring with an HF superconductor
the quantity $\Delta \Phi / \Phi_0 T$ is two orders of magnitude larger than in absence of the HF metal.

In what follows we propose a S-N-S system in which the weak link (N) is made of an
heavy-fermion metal with large thermopower $Q_{hf}$. It is demonstrated below that such a sys-
tem is potentially useful for making very sensitive thermosensors. The sandwich geometry is
assumed in which the N-S contacts lay in the $x - y$ plane, while the $z$-axis is perpendicular
to the contact. Let us assume that the parameters of the system are such that the supercon-
ducting current in the S-N-S weak link is described by the Josephson current relation, where
$I_S = I_c \sin \varphi$ with $\varphi = \varphi_L - \varphi_R$ and $\varphi_L(R)$ is the phase of the left (right) superconducting
bank. (The discussion of the latter condition is postponed to the end.) If the temperature
difference, $\Delta T \equiv T_L - T_R$, is applied at the contacts between the normal (HF) metal and
the left and right superconducting bank one can show that the phase $\varphi$ fulfills the equation
$$\frac{\partial^2 \varphi}{\partial t^2} - c_0^2 \left( \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} \right) + \frac{1}{\tau} \frac{\partial \varphi}{\partial t} + \omega_0^2 \left( \sin \varphi - \frac{Q_{hf} \Delta T}{I_c R_N} \right) = 0. \quad (2)$$

Here, $c_0$ is the Swihart velocity, $\omega_0 (\equiv c_0 / \lambda_J) = \sqrt{2 | e | I_c / \hbar C}$ is the Josephson plasma
frequency, $I_c$ is the critical current of the contact, $C$ is the capacity of the contact, $\tau = R_N C,$
$R_N$ is the resistance of the contact, and $\lambda_J$ is the Josephson penetration depth. From
Eq.(2) it is seen that the term $Q_{hf} \Delta T / R_N$ acts as a fixed external current $I$ in the standard
Josephson contact. Based on this analogy a number of physical phenomena based on Eq.(2)
can be studied but in this short note we analyze a few of them only.

Thermosensors. If the temperature difference fulfills the condition $\Delta T > \Delta T_c = I_c R_N / Q_{hf}$ the voltage on the contact oscillates with the frequency (related to the average voltage $< V > = \hbar \omega / 2 | e |$)
$$\omega = \frac{2 | e |}{\hbar} R_N I_c \sqrt{(\Delta T / \Delta T_c)^2 - 1}. \quad (3)$$

This relation, which is an analogon of the nonstationary Josephson effect, was first derived
in Ref.\cite{6}.

The peculiarity of the HF system is that the threshold temperature difference is very
small, and since $\Delta T_{c,hf} \sim Q_{hf}^{-1}$ it is practically 100 times smaller than for standard metals.

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For instance if the system operates at \( T = 2 \text{ K} \) one has \( Q_{hf} \sim 10^{-6} \text{ V/K} \) and if the HF metal is characterized by the small value of \( I_c R_N = V_c \sim (10^{-10} - 10^{-13}) \text{ V} \) then \( \Delta T_{c,hf} \sim (10^{-4} - 10^{-7}) \text{ K} \). As a comparison, by using as the weak link (N) a standard metal with \( Q \sim 10^{-8} \text{ V/K} \) (at the same temperature) one obtains \( \Delta T_c \sim (10^{-2} - 10^{-5}) \text{ K} \). The latter value is at least by two orders of magnitude larger than in the case of an HF metal. From this analysis one concludes, that the small value of \( \Delta T_{c,hf} \) opens a possibility of *measuring very small temperature difference*. The latter can be done by measuring the average voltage on the junction, or by measuring the frequency of the emitted radiation. On such a ground one can make *thermosensors*. One expects also that by applying low-frequency radiation on the contact one can generate small temperature difference in it.

An very interesting possibility for the manifestation of thermoelectric effects in S-N-S systems with HF metals with the weak link can be realized in the presence of a longitudinal ultrasound. Due to the large Grüneisen parameter, \( \Omega_{hf} \sim 10^2 \), the longitudinal ultrasound produces the temperature gradient oscillation with the amplitude

\[
\delta T \approx 2\pi \Omega_{hf} T u_0 / \lambda.
\]

Here, \( \lambda \) is the wave-length of the sound and \( u_0 \) is the atomic displacement due to the sound propagation. For the typical experimental value\(^\text{[3]}\) of \( \lambda \sim 10^5 \text{ Å} \) and by assuming for \( u_0 \sim (0.1 - 0.01) \text{ Å} \) then the amplitude of the temperature oscillation is \( \delta T \sim (10^{-3} - 10^{-4}) \text{ K} \), i.e. one has \( \delta T > \Delta T_{c,hf} \). The latter inequality tells us that the longitudinal sound can generate voltage oscillations. This effect will be elaborated elsewhere\(^\text{[4]}\).

Since the fixed value of \( \Delta T \) at the S-N-S contact plays the role of the fixed external current in S-N-S weak links, then the effects of magnetic field, pinning centers, etc. are interrelated in these two phenomena. Various such effects will be studied elsewhere\(^\text{[5]}\).

In the above analysis it was assumed that the S-N-S system, with a HF metal as the weak link (N), is described by the Josephson current relation. In order to get a small value of \( \Delta T_c \) it was also assumed that the voltage \( V_c(\equiv I_c R_N) \) is small. These two conditions can be realized in S-N-S systems with long spacing between superconducting banks, i.e. \( L \gg \xi_N =\)
(hD/2πT)^{1/2} where ξ_N is the coherence length of the weak link material (HF metal) and D is the diffusion coefficient. In that case one has I_S R_N \approx (4\Delta^2 L / | e | T \xi_N) \exp(-L/\xi_N) \sin \varphi^8. In many applications of S-N-S weak links it is necessary that the critical voltage V_c is comparable with the values in Josephson tunnel junctions. For that purpose the length of the weak link material must be short, i.e. L < (2 − 4)ξ where ξ is the coherence length of the weak link (HF) material.

In conclusion we argued that the S-N-S weak links based on heavy-fermion normal metals as the N part can be useful for thermosensors. This property is due to the large thermopower of the HF metals, like for instance in UPt_3, which is two orders of magnitude larger than in standard alkali metals. Due to the large Grüneisen parameter in HF metals the longitudinal ultrasound can generate voltage oscillation in S-N-S systems, thus opening new possibilities for applications. Similar effects are expected with other Kondo systems as the weak link.

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