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Giant Nernst effect in heavy-electron metals

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Abstract

Recent studies of the Nernst effect in a number of heavy-fermion systems have led to a previously unsuspected result. In some circumstances, the Nernst signal of quasi-particles becomes very large and can easily overwhelm the well-known Nernst effect produced by the movement of the superconducting vortices under the influence of a thermal gradient. In particular, the Nernst coefficient attains an exceptionally large magnitude in the ordered states of URu_2Si_2 and $PrFe_4P_{12}$. In all these cases, the order of magnitude of the Nernst signal appears compatible with the Boltzmann picture which links the Nernst coefficient to the energy-dependence of the Hall angle.
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1. Introduction

The Nernst effect, the generation of a transverse electric field by a longitudinal thermal gradient has attracted much attention since the observation of a finite Nernst signal in the normal state of high-T_c cuprates [1]. This uncommon transport coefficient is known to be enhanced in presence of vortex movement induced by thermal gradient in the vortex-liquid state of a type II superconductor [2]. In metals, on the other hand, due to a phenomenon dubbed Sondheimer cancelation [3], the Nernst coefficient, while much less explored, was believed to be small.

During the last few years, this belief has been countered by a host of experimental evidence. Several studies have established that Nernst effect in a metal can become quite large. While a rigorous interpretation of the Nernst data remains a challenge to the theory, the order of magnitude of the Nernst coefficient is compatible with the rough estimate obtained using a Boltzmann picture. A simple argument indicates that a dilute liquid of heavy quasi-particles with a long mean-free-path should generate a large Nernst signal with possible applications for thermo-electric cooling at low temperatures.

2. Ambipolar Nernst effect

The study of $NbSe_2$ [4] revealed that a finite negative Nernst signal persists at temperatures well above $T_c = 7.2\,K$. The maximum in the Nernst signal occurs when the contribution of hole-like and electron-like carriers to the Hall coefficient cancel out and the system becomes accidentally compensated. This result recalls that in a multi-band metal the Sondheimer cancelation is not valid and the flow of quasi-particles of opposite charge in presence of a thermal gradient can lead to an enhanced Nernst signal. This phenomenon known as the ambipolar Nernst effect, has been known since a long time ago in semi-conductor physics [5].

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3. Nernst effect in heavy-fermion metals

In general, heavy-fermion compounds are multi-band metals and therefore the existence of a finite Nernst signal is not a surprise by itself. As seen in Fig. 1, in many cases, the magnitude of the Nernst effect can become orders of magnitude larger than what was found in $NbSe_2$. This simply reflects the smallness of the Fermi energy which sets an energy scale roughly the inverse of the thermoelectric coefficients of the system. In the case of the heavy-fermion superconductor $CeCoIn_5$, the quasi-particle Nernst signal easily overwhelms the vortex signal associated with the superconducting transition [6]. This large Nernst coefficient ($\sim 1\,\mu V/KT$) appeared to be confined to a region of the (H,T) plane where other transport properties of the system display a non-Fermi liquid behavior. Further exploration of heavy-fermion metals led to the discovery of cases with an even larger Nernst coefficient. URu_2Si_2 is notorious for the presence of a mysterious electronic order below $T_0 = 17.5\,K$ [8]. It has been recently found that this ordering leads to a Nernst coefficient of a large ($\sim 4\,\mu V/KT$) magnitude [9]. The exploration of $PrFe_4P_{12}$ which is believed to present an antiferroquadrupolar (AFQ) ordering below $T_0 = 6.5\,K$ [10], revealed an even larger Nernst coefficient in the ordered state ($\sim 50\,\mu V/KT$) [11].

4. Correlation between the Nernst coefficient and the Hall angle

In the Boltzmann picture the Nernst coefficient tracks the energy dependence of the tangent of the Hall angle ($\tan\theta_H = \rho_{xy}/\rho_{xx}$) at the Fermi level [3,12]:

$$\nu = \frac{1}{B}\frac{\pi^2}{3}\frac{k_B^2 T}{e}\frac{\partial \tan\theta_H}{\partial\varepsilon}\Big|_{\varepsilon_F}, \tag{1}$$

where k_B and e are, respectively, the Botzmann constant and the fundamental charge. Since in a first approximation,

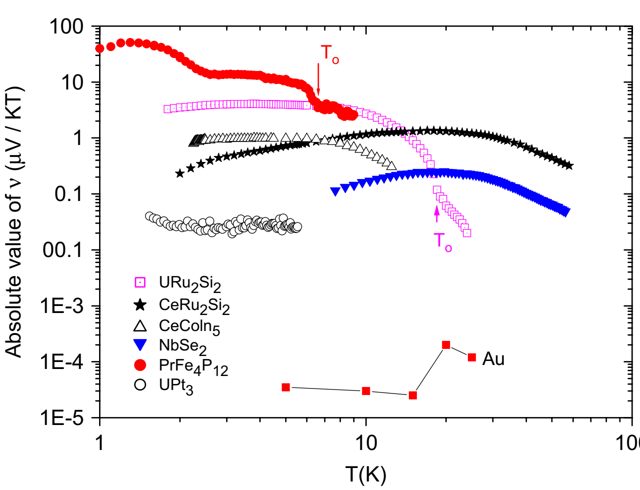

Fig. 1. Nernst coefficient of a number of heavy fermion compounds in the zero-field limit. For comparison, the figure displays data for gold and $NbSe_2$, a multi-band metal.

this energy derivative is just proportional to $\tan\theta_H/\varepsilon_F$, a combination of a large Hall angle and a small Fermi energy can lead to a very large Nernst signal. The cases mentioned above seem to corroborate this picture.

The non-Fermi liquid state in $CeCoIn_5$ is characterized by a large Hall coefficient [13] and a large effective mass [7] (indicative of the proximity of a quantum critical point).

In both URu_2Si_2 and $PrFe_4P_{12}$, ordering leads to a drastic drop in the carrier density and an enhancement of the electronic mean-free-path, the combination of these two factors leads to a spectacular increase in the Hall angle. In both cases, the residual quasi-particles of the ordered state still present a renormalized mass. The small Fermi wave–vector and the large effective mass of the quasi-particles in the ordered state have been directly observed by de Hass van Alphen studies [14,15]. These two features conspire to keep the Fermi energy small. Therefore, according to Eq. (1), a large Nernst coefficient is expected to emerge below the ordering temperature. The ordered state of these two compounds can be assimilated to a clean heavy-fermion semi-metal providing the three independent ingredients of a giant Nernst signal: a low carrier density, a large mass enhancement and a long mean-free-path. Further studies of the Nernst coefficient in more familiar heavy-fermion semi-metals such as CeNiSn would tell if these are the only ingredients needed to create a giant Nernst coefficient.

5. Towards an Ettingshausen refrigerator

Besides its fundamental aspect, the search for the origins of a giant Nernst signal is interesting due to its potential applications. An Ettingshausen cooler [16] can be conceived using a compound with a thermomagnetic figure of merit ($Z'T = N^2T/\kappa\sigma$) approaching unity, where $N = \nu/B$ is the Nernst signal and κ and σ are, respectively, thermal and electric conductivities. For a metal, thermal conductivity is expected to be dominated by the electronic contribution at low temperatures and therefore, the Wiedemann–Franz law translates this requirement to $N \approx 155\,\mu V/K$. The case of $PrFe_4P_{12}$ indicates that this magnitude may be reached in a clean heavy-fermion semi-metal.

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