Application Note

Measuring Thomson Effect in $YbInCu_4$ at Cryogenic Temperatures

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Introduction

In this application note, we show how the thermoelectric cooling performance at low temperatures can be improved by utilizing the Thomson effect in a specific material. By directly manipulating charge entropy through an electronic phase transition, we achieve a temperature span of over 5 K at 38 K. Alongside traditional Peltier-effect-based methods, this work introduces a new strategy to enhancing thermoelectric coolers and opens up new possibilities for solid-state cooling technologies. The measurements were conducted using Oxford Nanoscience's **Teslatron**PT system.

Motivation

Modern thermoelectric research is largely focused on improving cooling technologies, particularly for applications in low-temperature environments and solid-state refrigeration. Traditional thermoelectric coolers typically rely on the Peltier effect and the figure of merit (ZT), which imposes limitations on their performance especially at low temperatures. The main challenge is achieving a wide temperature span while also ensuring efficiency and stability. Since the figure of merit depends on the absolute temperature as well, enhancing Z value is crucial for low-temperature applications. Although William Thomson (Lord Kelvin) predicted a cooling effect within the bulk material (unlike the cooling effect at the junction based on the Peltier effect), the Thomson component of thermoelectric cooling remains underexplored.

Conventional thermoelectric materials show only modest Thomson coefficients and limited cooling performance, because of the small charge entropy change in nearly-free electrons. To improve the Thomson effect, we explore electronic phase-transition-based systems, where significant changes in entropy can enhance cooling. Our approach aims to utilize phase transitions in charge carriers to increase electronic entropy, thereby boosting the Thomson coefficient and overall cooling capacity. This strategy could significantly broaden the temperature range achievable by thermoelectric coolers and provide a new direction for advancing solid-state cooling technologies.

Methods

In this experiment, all transport properties were measured on the same sample using a cryostat's sample mount over a temperature range of 4 to 300 K with a 2 T magnetic field. To ensure stable thermal contact and reduce temperature fluctuations, the sample and thermocouple at the hot end were attached to a copper heat sink using electrically insulating epoxy. To maintain a large cooling capacity and counteract temperature variations, the copper block of the heat sink was connected to the cryostat chamber wall via spring clips. The proportional-integral-derivative (PID) parameters for temperature control of the heat sink were optimized to stabilize the hot-end temperature.

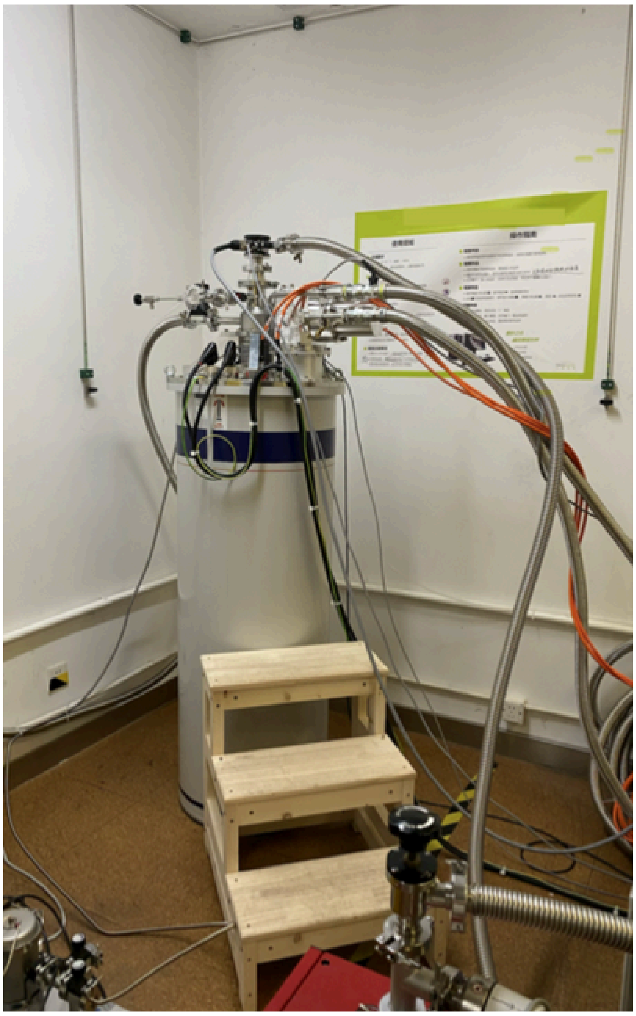

Fig.1 ***Teslatron****PT Cryofree superconducting magnet system in the lab.*

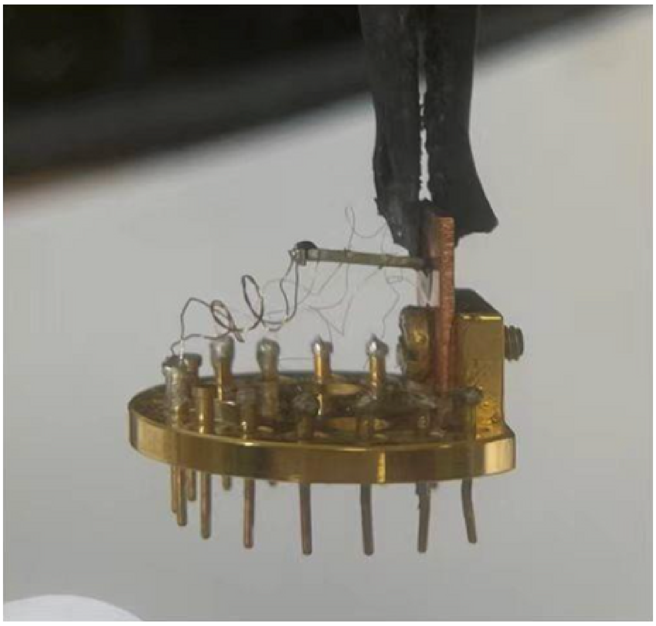

Fig.2 The sample.

Voltages, currents, and temperatures were measured using copper leads and type-T or type-E thermocouples (30 μm in diameter) that were attached to the sample. Isothermal resistivity and carrier concentration were measured using linear four-probe and DC van der Pauw methods, respectively, under helium exchange gas at a pressure of 0.7 atm. The Seebeck coefficient was measured by determining the thermopower as a function of temperature difference (0.3–3 K), induced by applying different currents to a thin-film resistor attached to the sample.

Experimental Results

In this work, we demonstrate the concept of utilizing Thomson effect for advancing thermoelectric cooling in $YbInCu_4$ that directly manipulated the entropy of charge carriers. Different from the lattice/magnetic transitions, this type of phase transition instead induces a direct manipulation to the entropy of charge carriers (working medium) for a significant increase in $\tau/T=d\alpha/dT$ up to 10 $\mu V/K^2$, and eventually enables a demonstration in devices of a steady

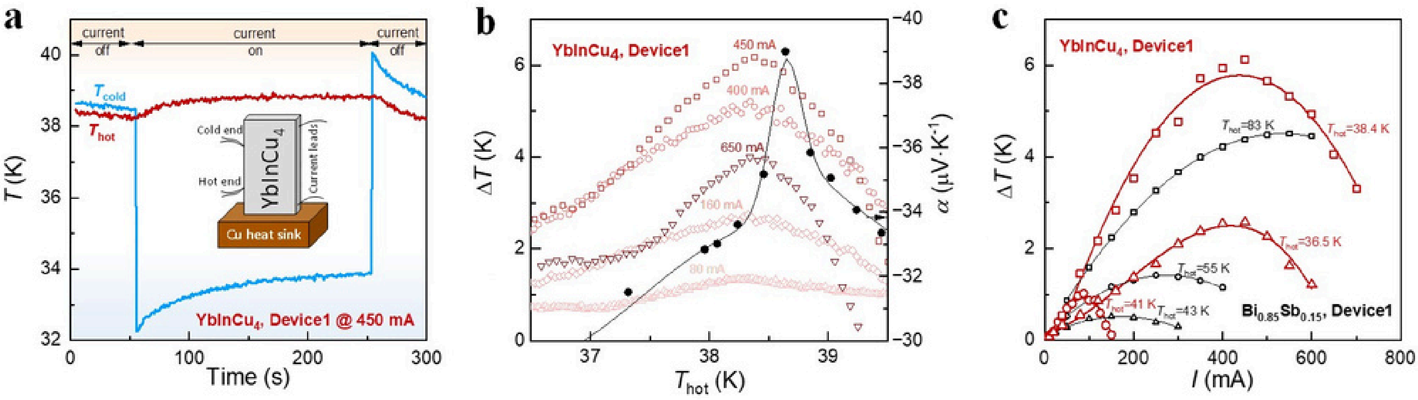

Fig.3 A typical temperature profile (a) and hot-side temperature-dependent temperature span (ΔT) and Seebeck coefficient for Device1 (b), Current dependent ΔT for $YbInCu_4$ - and $Bi_{0.85}$ $Sb_{0.15}$-based coolers at different hot-side temperatures (c).

temperature span of >5 K from ~38 K (Fig. 3a-b). This corresponds to a DT/T_{hot} of ~15%, which is comparable to that of 20% for a conventional Peltier cooler (DT=60 K from T_{hot} =300 K). This work illustrates a new approach for advancing thermoelectric coolers in addition to the improvement of *ZT* and illustrates great potential for extending solid-state thermoelectric cooling applications to cryogenic temperatures.

A large Thomson effect can be/ most effectively achieved through an electronic phase transition, as compared to other types of transitions, which is observed in certain materials around 40 K. At cryogenic temperatures, this novel thermoelectric cooler demonstrates significantly better performance compared to conventional Peltier coolers, such as those based on Bi_{1-x} Sb_x alloys, as illustrated in Fig. 3c. This highlights its promising potential for electronic cooling using the Thomson effect.

While much research on thermoelectrics has focused primarily on increasing the *ZT* value to improve device efficiency, the work by Chen et al. introduces a novel approach that utilizes unique electronic phase transitions and the Thomson effect to enhance thermoelectric cooler performance. This study also underscores the considerable potential of solid-state thermoelectric cooling for cryogenic applications.

Conclusion

In this work, we demonstrate the significant enhancement of the Thomson effect in $YbInCu_4$ due to an electronic phase transition, revealing a temperature-normalized Thomson coefficient (τ/T) of ~10 μV/K^2, compared to the conventional value of $\tau/T < 2$ μV/K^2. This strong Thomson effect, in combination with the Peltier effect at the junction, enables a steady temperature span greater than 5 K from ~38 K, effectively doubling the cooling capability of state-of-the-art Peltier coolers.

This research presents a new direction for advancing thermoelectric technologies and highlights the substantial potential for thermoelectric cooling at low temperatures. The findings open up future opportunities for research and applications in thermoelectric cryogenic cooling, enabling the development of more efficient cooling systems for low-temperature environments. In addition to the material studied, other materials with strong electronic interactions and phase transitions at or below room temperature may also hold promise for similar advancements.

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About the Lab

The Thermoelectric group in the Department of Materials Science and Engineering at Tongji University is dedicated to advancing both the scientific understanding and technological development of thermoelectrics. Their research emphasizes the fundamental physics, chemistry, and material science behind thermoelectric phenomena. With nearly two decades of experience in the field and active collaborations worldwide, the team is committed to driving the commercialization of thermoelectric technologies for power generation using waste heat and novel Peltier cooling applications. They believe the potential of thermoelectrics is limitless, since temperature gradients exist everywhere. Motivated by this vision, they strive to contribute to a cleaner and greener world.