Large mass enhancement in RbOs$_2$O$_6$

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Abstract

Heat capacity measurements on the recently discovered geometrically frustrated $\beta$-pyrochlore superconductor RbOs$_2$O$_6$ ($T_c = 6.4$ K) yield a Sommerfeld coefficient of 44 mJ/mol K$^2$. This is about 4 times larger than the one found in band structure calculations. In order to specify the enhancement due to electron-electron interactions, we have measured the electron-phonon enhancement. By a suitable analysis, an electron-phonon coupling constant $\lambda_{ep} = 1 \pm 0.1$ is derived from the specific heat jump at $T_c$. This leaves a significant additional $\lambda_{add} = 2.1 \pm 0.3$ for enhancement due to other mechanisms, possibly related to the triangular lattice. To arrive at these results, an appropriate analysis method for bulk thermodynamic data based on the condensation energy was applied.

Key words: RbOs$_2$O$_6$, superconductivity, correlation, DOS enhancement, thermodynamic properties

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Long standing interest in the pyrochlores stems from their inherent geometrical frustration due to the metal ions forming a network of corner-sharing tetrahedra. Thus, metallic pyrochlores constitute ideal systems to study to what degree itinerant electrons are affected by a lattice which is known to cause geometrical frustration for interactions among localized magnetic moments. For similar reasons, the superconductivity recently found in RbOs$_2$O$_6$ has been of considerable interest. RbOs$_2$O$_6$ is one of only four pyrochlore superconductors known to date. These are the $\alpha$-pyrochlore Cd$_2$Re$_2$O$_7$ and the $\beta$-pyrochlores AOs$_2$O$_6$, where A = Cs, Rb, or K.$^{[1,2,3]}$ RbOs$_2$O$_6$ is a conventional $s$-wave superconductor with a critical temperature $T_c = 6.4$ K.$^{[4,5,6,7]}$ In this short paper, we provide evidence for an additional electronic mass enhancement beyond the contribution from the coupling to phonons. Furthermore, the basic thermodynamic parameters of RbOs$_2$O$_6$ are extracted.

Specific heat measurements on RbOs$_2$O$_6$ show that the residual Sommerfeld coefficient in the superconducting state $\gamma_t$ and the normal-state coefficient $\gamma$ vary among the various samples measured. The variation is consistent with the presence of a second metallic component, and subsequent x-ray diffraction analysis has confirmed the presence of OsO$_2$ in the samples. We have therefore developed a suitable quantitative method to analyze thermodynamic data when dealing with a superconducting sample containing a metallic second phase. Since the analysis is based on the condensation energy of the superconductor of interest, we call it condensation energy analysis (CEA). It involves integrating the heat capacity to obtain the condensation energy which is a reliable measure of the superconducting fraction. From the systematic variation of the thermodynamic parameters on the superconducting fraction it is possible to extract the properties of the pure sample.$^{[7]}$

According to the CEA, the superconducting electronic specific heat $C_{es}$ is extracted from the measurement by $C_{es}(T) = \eta_m^2 \Delta C_p + \gamma_1 T$. Here, $\eta_m$ is the superconducting mass fraction, $\Delta C_p = C_{0T} - C_{12T}$ is the difference in heat capacity between the superconducting and normal state, and $\gamma_1$ is the Sommerfeld

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coefficient of pure RbOs$_2$O$_6$. $\gamma_1$ turns out to be $\gamma_1 = 79 \mu J/g/K^2$ ($44 mJ/mol_{l.u.}/K^2$) and this results in $C_{es}$ shown in Fig. 1. The sample shown in the figure has a mass fraction of RbOs$_2$O$_6$ of $\eta_m = 74.9\%$, corresponding to a volume fraction of 82.6%. Further thermodynamic parameters obtained from the measurements by CEA are listed in Table 1.

After having determined the intrinsic Sommerfeld coefficient $\gamma_1$ of RbOs$_2$O$_6$, it is possible to analyze the specific heat anomaly at $T_c$. The normalized specific heat jump $\Delta C_p(T_c)/(\gamma_1T_c) = 1.9$ is significantly larger than that for a weak coupling superconductor. It corresponds to an electron-phonon coupling constant $\lambda_{ep} = 2 \int_0^\infty \alpha^2 F(\omega) d\omega \approx 1$, where $\alpha^2 F(\omega)$ is the electron-phonon spectral density. Thus, RbOs$_2$O$_6$ is a superconductor in the intermediate-coupling regime.

![Fig. 1. Superconducting electronic specific heat of RbOs$_2$O$_6$.](image)

With the calculated band Sommerfeld coefficient $\gamma_b = 17.8 \mu J/g/K^2$ of RbOs$_2$O$_6$ from Ref. [9], the present result indicates a significant enhancement of the electronic specific heat of $(1 + \lambda_{ep} + \lambda_{add}) = (79.1 \mu J/g/K^2)/(17.8 \mu J/g/K^2) \approx 4.4$. This enhancement surpasses the one found in Sr$_2$RuO$_4$ of about 3.8 by 16% [10]. Additional to the electron-phonon enhancement $\lambda_{ep}$ there is a strong enhancement of unknown origin $\lambda_{add}$ $\approx 2.4$. We use the band structure $\gamma_0$ from another calculation to estimate the uncertainty in this additional enhancement: Saniz et al. (Ref. [10]) have calculated the band Sommerfeld coefficient for KO$_2$O$_6$, which is 18% higher than the one calculated in Ref. [9]. Assuming these 18% to be the uncertainty in $\gamma_0$ for RbOs$_2$O$_6$ results in $\lambda_{add} \approx 2.1 \pm 0.3$. In view of a calculated Stoner enhancement of the magnetic susceptibility of roughly 2,[9] we speculate that the additional enhancement is due to spin correlation effects.

In summary, we apply the CEA to RbOs$_2$O$_6$ to extract its intrinsic thermodynamic properties. Among other parameters it allows us to precisely determine the electron-phonon enhancement $\lambda_{ep} = 1 \pm 0.1$, i.e. RbOs$_2$O$_6$ is an intermediate-coupling superconductor. Furthermore, RbOs$_2$O$_6$ has a high Sommerfeld coefficient for a pyrochlore of 44 mJ/mol$_{l.u.}/K^2$ and thus a remarkably large enhancement over the calculated band coefficient of 3.8 to 4.4. In addition to the enhancement due to the coupling to phonons, there is thus an unusually high enhancement of the density of states due to other mechanisms $\lambda_{add} = 2.1 \pm 0.3$. We speculate that the origin of this mass enhancement lies in the 3-dimensional triangular nature of the pyrochlore lattice.

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| Table 1 | Thermodynamic parameters of RbOs$_2$O$_6$. |
|---------|-------------------------------------|
| Parameter | Value |
| $\xi, \lambda_{ep}(0 K)$ | 74 Å, 252 nm |
| $\kappa(T_c)$, $\kappa(0 K)$ | 23, 34 |
| $\Delta C_p(T_c)/(\gamma_1T_c)$ | 1.9 |
| $\lambda_{ep}$, $\lambda_{add}$ | $1 \pm 0.1, 2.1 \pm 0.3$ |
| $b/T_c$ | $(0.175 \pm 0.005) K^{-2}$ |
| $\Delta U_1(0 K)$ | $860 \mu J/g$ (483 mJ/mol$_{l.u.}$) |
| $H_c, H_{cs1}, H_{cs2}(0 K)$ | 1249, 92, 60000 Oe |
| $-dH_c/dT_c$, $-dH_{cs2}/dT_c$ | 369, 12000 Oe/K |
| $Q \equiv -T_0 \frac{dH_c}{dT_c}$ | $3.79 \pm 0.05$ |
| $k_B T_c/(\hbar\omega_{ph})$ | 0.06 |
| $2\Delta(0 K)/(k_B T_c)$ | 3.87 |
| $1/(8\pi) : (\gamma_1 T_c^2)/\Delta U_1$ | 0.15 |

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