HEAVY QUASIPARTICLES AND PSEUDOGAP FORMATION IN $YbAl_3$: OPTICAL CONDUCTIVITY STUDY*

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We have measured the optical conductivity $\sigma(\omega)$ of the mixed-valent compound $YbAl_3$. $\sigma(\omega)$ exhibits a mid-infrared peak centered at 0.15-0.2 eV, which becomes more pronounced with decreasing temperature (T). In addition, a strong depletion of the spectral weight, *i.e.*, a pseudogap formation, is observed in $\sigma(\omega)$ below $\sim$ 0.1 eV. A comparison of $\sigma(\omega)$ with the dc conductivity indicates the existence of an extremely narrow Drude peak at very low energy. Energy-dependent effective mass and scattering rate of the carriers are evaluated from the optical data, which indicates the formation of a heavy-mass Fermi liquid state within $\sim$ 40 meV from the Fermi level. These observations are discussed in terms of the hybridization of a conduction band and a narrow $4f$ band.

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$YbAl_3$ is a valence-fluctuating (VF) compound which is gaining increasing interest recently [1–3]. At low temperature (T), de Haas–van Alphen oscillations of $YbAl_3$ were clearly observed, indicating the formation of heavy mass Fermi liquid with effective masses of 14–24 m_0 [2]. The magnetic susceptibility (χ) shows a local moment (Curie–Weiss) behavior at high T and

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a broad maximum at $T_{\max} \sim 120$ K, which is typical of VF compounds with a Kondo temperature of ~ 500 K. Typically, properties such as χ and the electronic specific heat (C_e) for such VF compounds show T dependences that are very similar to predictions of the Anderson impurity model (AIM). However, recent work on high quality single crystalline $YbAl_3$ has shown that $\chi(T)$ and $C_e(T)$ below ~ 40 K deviate from the predictions of AIM. In the same T range, the resistivity shows a T^2 dependence, *i.e.*, a Fermi liquid property. These observations suggest that effects of the Yb lattice may be responsible for the deviation from AIM [3].

In this work, we use optical spectroscopy to probe the interesting electronic structures of $YbAl_3$ near the Fermi level ($E_{\rm F}$). The $YbAl_3$ and $LuAl_3$ samples used in this work were high-quality single crystals grown with a self-flux method [1]. The optical reflectivity $R(\omega)$ was measured in the range 20 meV–30 eV under a near-normal incidence. Optical conductivity $\sigma(\omega)$ was obtained from a measured $R(\omega)$ using Kramers–Kronig relations [4]. For low-energy extrapolation, a Hagen–Rubens formula was used [4]. More details of the optical experiments can be found elsewhere [5].

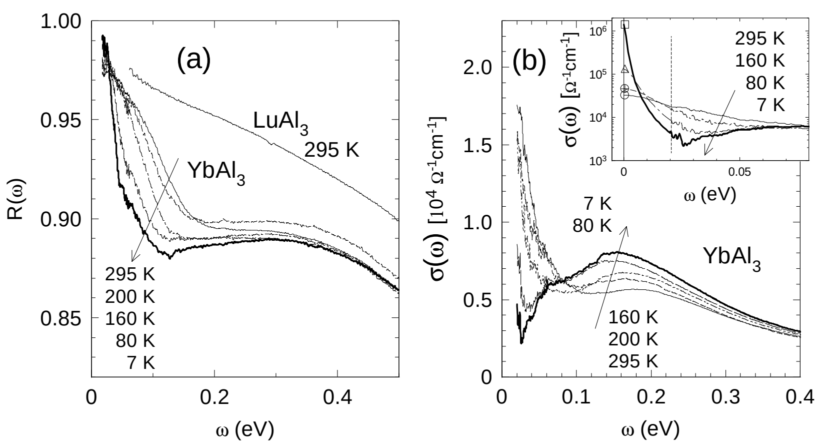

Fig. 1. (a) Infrared optical reflectivity $R(\omega)$ of $YbAl_3$ and $LuAl_3$. (b) Optical conductivity $[\sigma(\omega)]$ of $YbAl_3$. The inset compares low-energy $\sigma(\omega)$ with the corresponding $\sigma_{\rm dc}$, indicated by the symbols on the vertical axis (note the logarithmic scale). The $\sigma(\omega)$ curves below 0.02 eV are extrapolations.

Figure 1(a) shows $R(\omega)$ of $YbAl_3$ at temperatures $7\text{ K} \leq T \leq 295$ K, and that of non-magnetic $LuAl_3$ at 295 K. $YbAl_3$ has a broad dip in $R(\omega)$, which is strongly T-dependent and becomes more pronounced with decreasing T. In contrast, $LuAl_3$ has no such feature, indicating that the dip for $YbAl_3$ results from Yb $4f$-related states near $E_{\rm F}$. Figure 1(b) shows $\sigma(\omega)$ of $YbAl_3$. It is seen that the broad dip in $R(\omega)$ gives rise to a strong mid-IR peak in $\sigma(\omega)$, which grows with decreasing T. At the same time, the spectral weight below the mid-IR peak energy is gradually depleted with decreasing T. This spectral depletion in $\sigma(\omega)$, *i.e.*, a pseudogap formation, shows that the density of states in the region 10-50 meV away from E_F becomes small at low T. This may appear striking since $YbAl_3$ is a good metal, with a dc conductivity σ_{dc} exceeding 10^6 $\Omega^{-1}cm^{-1}$ at 7 K [1]. σ_{dc} and $\sigma(\omega)$ are compared to each other in the inset of Fig. 1(b), where σ_{dc} are indicated by the symbols on the vertical axis. It is immediately apparent that a narrow Drude peak, *i.e.*, a very sharp rise in $\sigma(\omega)$, should exist in the low-energy region below the measurement range of this work. A similar spectral feature was first reported for mixed-valent $CePd_3$ [6], and later for many other f-electron compounds [7]. The narrow Drude peaks in these works have been understood in terms of the electrodynamical response of a heavy-mass Fermi liquid, *i.e.*, a "heavy fermion plasma" [8]. Namely, the formation of a spatially coherent heavy fermion state leads to a large effective mass and a reduced scattering rate of the carriers. Since the scattering rate is directly related to the width of a Drude peak in $\sigma(\omega)$, it becomes extremely narrow, often observed in the microwave region [7].

In addition to the narrow Drude peak, the present data show two key features in $\sigma(\omega)$, namely the mid-IR peak and the pseudogap below ~ 0.1 eV. Again, similar features have been observed for many heavy fermion and mixed valent compounds. A generally accepted mechanism leading to such spectral features is a hybridization of wide conduction (c) band and a narrow f band. This c–f hybridization leads to the formation of a small energy gap, and the optical excitation of quasiparticles across this gap leads to a mid-IR peak in $\sigma(\omega)$. Heavy fermions arise when E_F is located slightly above or below the gap. It is noteworthy that the spectral variation between 7 K and 40 K (not shown) was much smaller than that between 40 K and 80 K. This may be regarded as evidence that the development of c–f hybridization state is complete below 40 K, which is consistent with the resistivity data showing a T^2 (Fermi liquid) dependence below 40 K.

In order to obtain more information about the electronic structures near E_F of $YbAl_3$, we apply the so-called "generalized Drude" analysis [7] to the present data. In this model, the energy-dependent scattering rate $1/\tau(\omega)$ and optical effective mass $m^*(\omega)$ of the quasiparticles can be evaluated from the optical spectra. Figure 2 shows the results. Below 80 K, $1/\tau(\omega)$ is strongly suppressed at energies below ~ 40 meV, where it shows approximately a ω^2 dependence. This strongly suggests the formation of a coherent Fermi liquid state. $m^*(\omega)$ below ~ 40 meV becomes large with decreasing T, reaching about 25 times the bare band mass at 7 K. The observed behaviors of $1/\tau(\omega)$ and $m^*(\omega)$ indicate that a Fermi liquid state with a heavy mass is formed within ~ 40 meV from E_F. The mass enhancement factor of 25 is close to the cyclotron masses of 14–24 m_0 deduced from the de Haas–

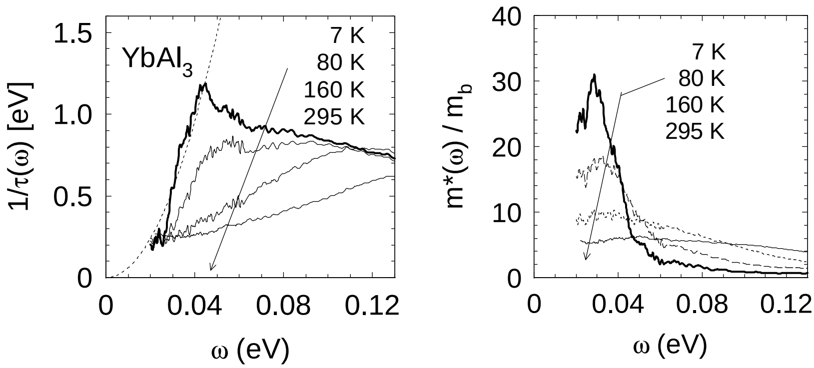

Fig. 2. Energy-dependent scattering rate $1/\tau(\omega)$ and effective mass $m^*(\omega)$ normalized by optical band bass m_b for $YbAl_3$, obtained using the generalized Drude model. The dotted curve in the left graph is guide to the eye, showing a ω^2 dependence.

van Alphen data [2]. The observed T dependences of $1/\tau(\omega)$ and $m^*(\omega)$ are quite similar to those previously reported for $CePd_3$ [6], where $\sigma(\omega)$ was measured to much lower energy (0.5 meV) than in the present work. Hence, although our measurement range is not sufficient to directly observe the narrow Drude peak in $\sigma(\omega)$, the present data appear to have captured important features of the heavy fermion dynamics in $YbAl_3$. Measurements in lower-energy region are in progress, to study the heavy fermion dynamics more quantitatively.

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