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A quantitative study of the dynamical conductivity of the heavy electron compounds $CeAl_3$ and UPt_3

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ABSTRACT

We report a temperature dependent calculation of the dynamical conductivity of two heavy electron compounds $CeAl_3$ and UPt_3. Heavy-electron systems are electrically conducting materials with peculiar low-temperature physical properties that distinguish them from ordinary metals. The range of temperature studied is from 1.2K to 10K. Marked difference in behavior is observed in this range. The results compare qualitatively well with experimental studies.

Key words*:* Dynamical conductivity, heavy electron compounds, low temperature, Fermi degeneracy temperature, f-orbitals, conduction-electron effective mass, Kramers-Konig relations.

INTRODUCTION

The class of materials called 'heavy electron compounds' including $CeAl_3$, UPt_3, $CeCu_2Si_2$, $CeCu_6$, UBe_{13}, and others show peculiar properties at low temperatures [1]. At high temperatures, these systems behave as a weakly interacting collection of *f*-electron moments and conduction electrons with quite ordinary masses; at low temperatures, the *f*-electron moments become strongly coupled to the conduction electrons and to one another, and the conduction-electron effective mass is typically 10 to 100 times the bare electron mass. The electronic specific heats and the Pauli paramagnetic susceptibilities are large. The Fermi degeneracy temperature, which marks the onset of the low-temperature regime for the specific heat and various properties, is of the order of 100 K in many of these compounds as opposed to 10,000 K and higher in ordinary metals. It can be said that the carriers in heavy-electron compounds behave more like protons or helium atoms than electrons. Hence the compounds belonging to this class are also called heavy-fermion compounds. They derive their properties from the partially filled f orbitals of rare-earth or actinide ions [2,3].

In this paper we report the calculation of the dynamical conductivity of the heavy electron compounds $CeAl_3$ and UPt_3. While $CeAl_3$ is superconducting at low temperatures, UPt_3 is neither superconducting nor magnetically ordered. Both these compounds have a hexagonal crystal structure, but the actinide UPt_3 displays an anisotropic resistivity between the *ab* plane and along the hexagonal *c* axis [4].

MATERIALS AND METHODS

Our calculation of the dynamical activity of these heavy-electron compounds is based on the model of *Millis and Lee* [5] as applied by Shikha et al. [6]. This model is believed to contain the essential physics of the currently interesting heavy-electron metals: a nonmagnetic ground state that behaves as a Fermi liquid with a large effective mass. This model defines two characteristic plasma frequencies - ω_p at high frequency and $\varpi *_p$ at low frequency. The plasma frequency $\varpi *_p$ is screened by the high frequency excitations defining the broad background in $\sigma_1(\omega)$ [7]. ω_p is the unscreened optical plasma frequency also identified in the generalized Drude model. σ and σ_1 are related by the equation

$\Gamma(\omega) = (\omega_p^2 / 4\pi)(\sigma_1 / |\sigma|^2)$

where Γ is called the scattering rate.We have earlier reported the calculations of Γ and ω_p [6,8].

The dynamical conductivity is given by

$$\sigma(\omega) = \sigma_1(\omega) + i\,\sigma_2(\omega) \quad (1)$$

where $\sigma_1(\omega)$ and $\sigma_2(\omega)$ are the real and imaginary parts of the dynamical conductivity, and are calculated using Kramers-Konig relations.

Table- 1 : Evaluation of σ_1 (ω) for $CeAl_3$ (in units of $10^4/\Omega$cm).

ω (cm^{-1})	T=1.2K	T=3K	T=5K	T=10K
10^{-2}	2.325	1.862	1.629	1.242
10^{-1}	2.356	1.875	1.629	1.242
10^{0}	2.304	1.889	1.676	1.265
10^{1}	1.954	1.856	1.604	1.200
10^{2}	1.862	1.820	1.556	1.186
10^{3}	1.716	1.803	1.508	1.172

Table- 2 : Evaluation of $\sigma_2(\omega)$ for $CeAl_3$ (in units of $10^4/\Omega$cm)

ω (cm^{-1})	T=1.2K	T=3K	T=5K	T=10K
10^{-2}	0.934	0.659	0.478	0.259
10^{-1}	0.916	0.642	0.462	0.240
10^{0}	0.900	0.633	0.455	0.236
10^{1}	0.895	0.627	0.443	0.228
10^{2}	0.887	0.610	0.430	0.217
10^{3}	0.868	0.608	0.428	0.204

Table- 3: Evaluation of $\sigma_1(\omega)$for UPt_3 (in units of $10^5/\Omega$cm)

ω (cm^{-1})	T=1.2K	T=3K	T=5K	T=10K
10^{-2}	2.486	2.405	2.322	2.239
10^{-1}	2.466	2.387	2.247	2.180
10^{0}	2.448	2.334	2.208	2.116
10^{1}	1.429	2.048	2.126	2.007
10^{2}	1.626	1.927	2.087	2.196
10^{3}	1.747	1.886	2.000	2.306

Table- 4: Evaluation of $\sigma_2(\omega)$ for UPt_3 (in units of $10^5/\Omega$cm)

ω (cm^{-1})	T=1.2K	T=3K	T=5K	T=10K
10^{-2}	1.072	1.003	0.872	0.527
10^{-1}	1.065	0.987	0.843	0.500
10^{0}	1.052	0.962	0.805	0.438
10^{1}	1.047	0.955	0.723	0.409
10^{2}	1.033	0.947	0.706	0.356
10^{3}	1.029	0.938	0.686	0.309

RESULTS AND DISCUSSION

The calculated values of $\sigma_1$and σ_2 are given in tables 1 – 4. The results show that their values decrease with increase in frequency ω.

From experimental measurements, *Awasthi et al.* [9, 10] found that the increase in resistivity with temperature at low temperatures at millimeter-wave frequencies is frequency dependent, but at high temperatures (above approximately 10K), the response is almost frequency independent. This implies that in the high temperature region, σ_2 is negligible compared to σ_1. Our results also show the same trend.

CONCLUSION

There are large no of optical experiments available on proto type heavy electron compounds. This paper is a part of our detailed investigative study of the eletromagnetic response of heavy electron compounds. We have particularly studied the two proto type fermion systems - $CeAl_3$ and UPt_3 . The results obtained by us for the prototype $CeAl_3$ and UPt_3 materials are very general and typical of a large variety of heavy-electron systems. Indeed, the formation of a narrow mode centered at zero frequency in $\sigma_1(\omega)$ at low temperatures is a common optical finger-print of heavy-electron systems in their highly correlated ground state. We sincerely expect our results to enhance the understanding of the behavior of the heavy electron compounds.

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