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Evaluation of effective mass and scattering rate for the heavy electron system UPt_3

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Abstract: *The present paper reports a temperature dependent calculation of effective mass and scattering rate for the compound* UPt_3. *It is a typical heavy electron compound. The calculation uses the Kramers-Konig relations within the model of Millis and Lee . The results are compared with reported experimental data.*

I. Introduction

UPt_3, a compound of uranium and platinum, belongs to the class of *heavy electron Systems* [1]. These are heavy-electron compounds showing surprising behaviours, particularly at low temperatures. They derive their properties from the partially filled f orbitals of rare-earth or actinide ions [2, 3]. The conduction electrons in these metallic compounds have effective masses of 100 to 1,000 times the free-electron mass as opposed to values of about 10 for transition metals thus behaving more like protons or helium atoms than electrons. The large effective mass is accompanied with large electronic specific heats, at low temperatures, and large Pauli paramagnetic susceptibilities. It is superconducting at low temperatures. The actinide UPt_3 has a hexagonal structure and displays an anisotropic resistivity, between the *ab* plane and along the hexagonal *c* axis [4]. Its resistivity $\rho(T)$ follows the T^2 law viz.

$$\rho(T) = \rho_0 + AT^2 \qquad (1)$$

at very low temperature. Besides $\rho(T)$, the magnetic susceptibility $\chi(T)$ and specific heat capacity $C_p(T)$ also show the typical heavy-electron behavior. From experimental measurements, it was found [5, 6] 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 regime, the scattering rate (Γ) is significantly larger than the millimeter-wave frequencies, and σ_2 is negligible compared to σ_1 , where the optical conductivity

$$\sigma(\omega) = \sigma_1(\omega) + i\,\sigma_2(\omega). \qquad (2)$$

In this paper, we present an evaluation of frequency and temperature dependent effective mass m^*, and scattering rate Γ at different temperatures for UPt_3.

II. Model and Formulation

Heavy-electron materials can be considered as metals with strongly correlated, yet delocalized electrons. A T^2 - dependence of $\rho(T)$ at low temperatures is usually taken as the criterion for the identification of Fermi-liquid behavior in heavy-electron systems. It is observed in these systems that an enormously large specific-heat coefficient γ implies an effective mass m^* of the quasiparticles, which is several hundred times the free-electron mass. The enhancement of the effective mass is understood to be due to the presence of localized *f* electrons in all heavy-electron systems. These may be *U* ions with 5 *f* electrons in UPt_3.

A comprehensive model for a theoretical understanding of the behavior of the heavy-electron compounds was developed by *Millis and Lee* [7]. As detailed in our earlier paper [8], there are two possible sources of scattering of electrons in these systems. One is the scattering of electrons from the impurities and the other is the scattering from boson fluctuations. Two characteristic plasma frequencies are then expected: the one at high frequency ω_p which identifies the uncorrelated conduction electrons, and the other $\varpi_p{}^*$ is at low frequency and associated with the heavy plasmons.

A method of estimating m^*/m_b together with the scattering rate Γ is to consider the low-frequency resonance arising from free carriers undergoing frequency dependent scattering. This means that the optical conductivity may be described by a so-called generalized Drude model [6, 9]. Obviously, the frequency dependence of Γ implies, through the Kramers-Kronig relation between σ_1 and σ_2, that m^* is also frequency dependent. The application of the generalized Drude model at different temperatures will permit the evaluation of the temperature dependence of m^* and Γ. Therefore the complex conductivity may be written as (*Thomas et al., 1988*)

$$\sigma(\omega) = (\omega_P{}^2/4\pi) / [\Gamma(\omega) - \iota\omega\{\mu^*(\omega)/m_b\}] \qquad (3)$$

where ω_p is the unscreened optical plasma frequency. A relationship between σ_1 , σ_2 , and Γ together with m^*/m_b is then obtained as follows:

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

and

$$m^*(\omega) / m_b = (\omega_P^2 / 4\pi)\ (\sigma_2 / \omega|\sigma|^2) \qquad (5)$$

III. Results and Discussions

The calculated values of m^*/m_b and Γ for UPt_3 are given in the Tables *1 & 2*. Our results for $m^*(\omega)/m_b$ indicates that its value decreases with increase in temperature (at low temperatures) as well as with increase in frequency. At 10 K, these values are *112.200, 96.8699, 84.8624 and 56.0854* respectively. Experimentally, at *10K* and above, $m^*(\omega)$ for UPt_3 ($T_k \sim 1.2$ K) saturates to an enhanced value of approximately $240\ m_e$ *(i.e.,* $m^* \sim 65m_b$*)*. The experimental data are taken from the works of *Sulewski et al.*[9] and *Donovan et al.*[11]. The quantitative difference with our theoretical results might indicate some more rigorous theoretical formulation.

Table- 1 : Evaluation of (m^*/m_b).

ω (cm^{-1})	**T = 1.2K**	**T = 3K**	**T = 5K**	**T = 10K**
1	130.869	118.568	102.699	88.786
2	128.769	114.689	100.233	84.235
3	125.339	110.059	98.453	80.176
4	122.669	108.680	96.563	75.878
5	120.112	106.002	93.335	70.686
6	118.689	104.868	91.036	68.870
7	117.002	102.698	89.668	62.532
8	115.655	100.698	87.224	60.026
9	114.223	98.273	85.666	58.889
10	112.200	96.869	84.862	56.085

Table- 2: Evaluation of $h\Gamma(\omega)$.

ω (cm^{-1})	**T=1.2K**	**T=3K**	**T=5K**	**T=10K**
1	0.02956	0.04351	0.06775	0.08886
2	0.03118	0.04418	0.06813	0.08923
3	0.03222	0.04552	0.06998	0.09124
4	0.03356	0.04677	0.07152	0.09227
5	0.03469	0.04886	0.07268	0.09377
6	0.03675	0.05009	0.07337	0.09448
7	0.03872	0.05118	0.07486	0.09593
8	0.03995	0.05212	0.07558	0.09634
9	0.04110	0.05318	0.07623	0.09772
10	0.04258	0.07741	0.07777	0.09995

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