Microwave Reflectivity of $CeRu_2Si_2$: Collective Excitations in the Electronic Fermi Liquid

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We present microwave reflectivity data (35–134 GHz) on the magnetically nonordering heavy fermion compound $CeRu_2Si_2$. In the Fermi liquid region at fields near to the metamagnetic transition ($B_c \cong 8$ T) we observe pronounced effects with a reflectivity change of several percent. The experimental features can be explained within an oscillator model in $\tilde{\epsilon}(\omega)$ and $\tilde{\mu}(\omega)$. The oscillator frequencies become soft at B_c. The relaxation frequencies $\Gamma^{\rm osc}_{\epsilon,\mu}(<\omega)$ are extremely small and point to long lived collective excitations. They are supposed to represent the propagation of a zero sound mode and spin waves.

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Heavy fermion systems are known for their extremely narrow band of quasiparticles at the Fermi level. It corresponds to an electronic mass renormalization $m^*/m_{\rm el}$ of more than 100 [1,2]. Though several of their low temperature properties can basically be understood within the context of Landau's Fermi liquid theory [3] many physical features remain unexplained until now. They are due to additional aspects like the electric charge of the quasiparticles, the crystalline anisotropy, and a large variety of different magnetic interactions [2,4].

If one follows the main ideas of Landau, a wide spectrum of collective excitations should be expected in a Fermi liquid [5]. While the low energy region $\omega < 1/\tau_{\rm hyd}$ contains the excitation of a hydrodynamic sound mode, so-called *first sound,* at higher frequencies $\omega > 1/\tau_{\rm hyd}$ *zero sound* modes and *spin waves* should propagate ($\tau_{\rm hyd}$ is the hydrodynamic relaxation time). They carry the essential information of different quasiparticle interactions.

In the case of heavy fermion systems theoretical works have predicted two zero sound modes: $\omega_0^a = \sqrt{6}T^*$ and $\omega_0^b = v_F q/\sqrt{3}$ [6,7]. Experimentally they have not been observed until now. Moreover, no theoretical or experimental evidence at all exists about the propagation of spin waves with respect to magnetically nonordering systems.

In this Letter we present the first results of microwave spectroscopy on the tetragonal heavy fermion system $CeRu_2Si_2$. They yield strong indications for the existence of a zero sound mode and spin waves in the electronic Fermi liquid region.

$CeRu_2Si_2$ displays pronounced metamagnetism at a critical field of $B_c \cong 8$ T while long range magnetic order is absent [8,9]. The metamagnetism is clearly connected to the anisotropy of the electronic Fermi liquid since this anomaly can only be observed when the magnetic field is aligned parallel to the tetragonal c axis [8]. The magnetic anomaly becomes more pronounced as the temperature decreases; below $T = 1$ K it saturates and thus a phase transition is prevented [10,11]. In contrast to the metamagnetism of magnetically ordering systems [12,13] no complete theory so far exists for the metamagnetic behavior of $CeRu_2Si_2$.

In our spectroscopic experiments we employed two single crystals which were grown by P. Lejay (CNRS, Grenoble). The quality of the samples has been probed several times before, with respect to their thermodynamic properties [10,14,15]. In this Letter we will only refer to the experimental results of the second sample. Its surface is 3×4 mm^2 in size (a-b plane) and it was polished up to optical quality.

The microwave setup was constructed for Faraday geometry ($\mathbf{B} \parallel \mathbf{k}$). Since a perpendicular incidence of radiation was chosen, the field coincides with the magnetic easy axis of the sample. The microwave frequencies (35–134 GHz) are generated by Impatt and Gunn sources and the reflected signal is analyzed by different types of high sensitivity Schottky diode detectors. This signal carries the information of the sample reflectivity $\Delta R(B,T)$. An absolute measurement of the reflectivity demands a comparison with a reference mirror; this was left out because of the associated experimental error. Since the microwave radiation propagates in a waveguide system, standing wave problems and waveguide mode conversion effects were precisely regulated out by additional mechanical and electronic devices. A detailed description of the setup will be published elsewhere [16].

The measurements were performed as a function of field and temperature at frequencies of 35, 55, 70, 99, and 134 GHz. At all frequencies significant effects in the reflectivity $\Delta R(B,T)$ were observed (0.5%–5%). Towards lower temperatures the anomalies are correlated to the critical field and exhibit a strongly frequency dependent line shape [Fig. 1(a)]. In addition, some small and sharp features in $\Delta R(B,T)$ were recorded at the lower frequencies [see horizontal arrows in Fig. 2(b)]. With rising temperature the resonantlike structures broaden and describe closed phase lines [Figs. 2(a) and 2(b)].

Since the microwave reflectivity shows a complex structure of excitations, we tried to find a general approach

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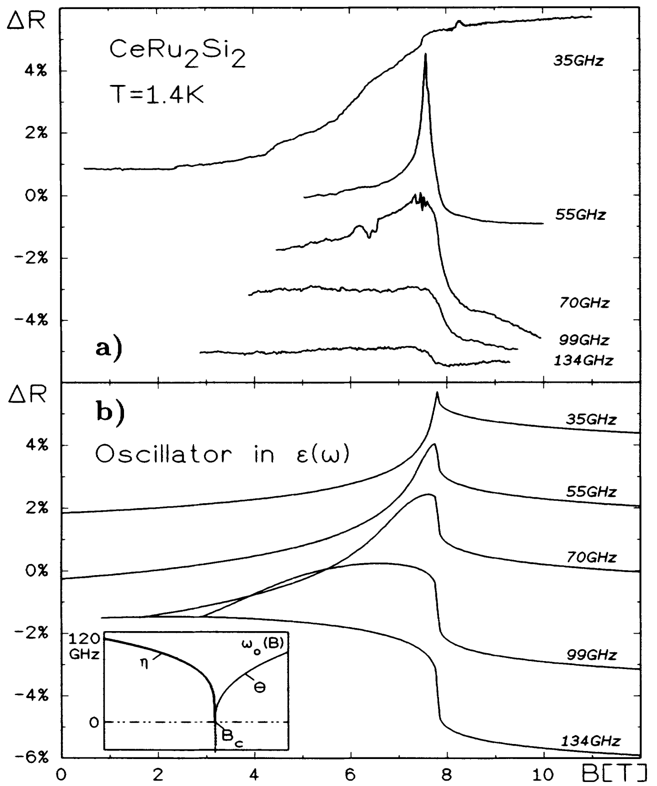

FIG. 1. (a) Microwave reflectivity $\Delta R(B)$ of $CeRu_2Si_2$ at $T=1.4$ K. Note the strong varying line shape with rising frequency. The critical field at $T=1.4$ K is $B_c(1.4\text{ K})=7.8$ T. (b) Calculated reflectivity $\Delta R(B)$ assuming an oscillator in $\tilde{\varepsilon}(\omega)$ [Eq. (1)]. The oscillator frequency ω_0^η becomes soft at $B\to B_c$. Inset: Function plot of $\omega_0^{\eta,\theta}=\omega_0^{\eta,\theta}(B)$. To avoid discontinuity in Eq. (1) ω_0^η leads to negative values above B_c.

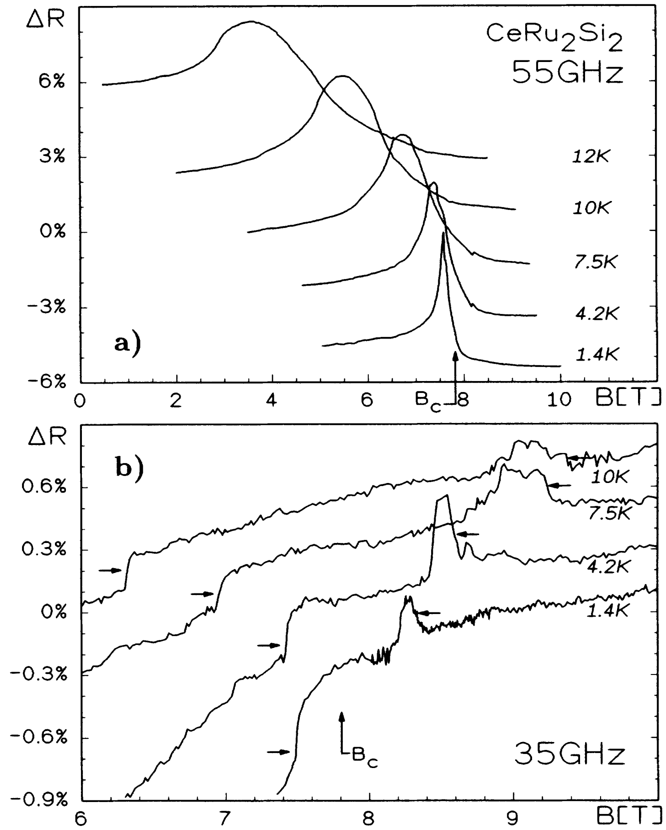

FIG. 2. (a) Temperature dependence of the 55 GHz anomaly. With rising temperature the resonantlike structure broadens and describes a closed phase line. (b) Temperature dependence of the small and sharp anomalies at 35 GHz (marked by horizontal arrows). The effects are symmetrically arranged around the critical field and can be explained with magnetic oscillators.

that describes the experimental data. Guided by the different line shapes and their temperature dependence we treated the dynamic character of the Fermi liquid in accordance with a soft-mode behavior at a phase transition.

Therefore the excitations below and above B_c shall be indicated with $\eta(\omega)$ and $\theta(\omega)$, respectively. The eigenfrequencies of $\eta(\omega)$ and $\theta(\omega)$, $\omega_0^\eta(B)$ and $\omega_0^\theta(B)$, will then tend to zero if B tends to B_c [inset, Fig. 1(b)]. The corresponding response is given by the dynamic susceptibilities, $\tilde{\varepsilon}(\omega)-1$ and $\tilde{\mu}(\omega)-1$. We found the best agreement with the experiment was by assigning a dielectric oscillator $\tilde{\varepsilon}_{osc}^\eta$ to the η excitations only. Adding a background Drude term one obtains for $\tilde{\varepsilon}(\omega)$

$$\tilde{\varepsilon}(\omega)=\tilde{\varepsilon}_{Dr}(\omega)+\tilde{\varepsilon}_{osc}^\eta(\omega)$$
$$=1-\frac{f_1\omega_{Pl}^2}{\omega(\omega+i\Gamma_{Dr})}+\frac{f_2\omega_{Pl}^2}{\omega[\omega_0^\eta(B)-\omega-i\Gamma_\varepsilon^\eta]}\,. \qquad (1)$$

We computed the reflectivity change choosing $\omega_{Pl}=2\pi\times20$ THz, $f_2=1-f_1=0.03$, $\Gamma_{Dr}=2\pi\times5$ THz, $\Gamma_\varepsilon^\eta=2\pi\times15$ GHz, $\omega_0^\eta(B)=\Delta_0[(B_c-B)/B_c]^{0.25}$ with $\Delta_0=2\pi\times120$ GHz [see Fig. 1(b)]. To avoid discontinuity the slope of $\omega_0^\eta(B)$ leads to negative values for $B>B_c$ [inset, Fig. 1(b)]. The obtained low value of the plasma frequency coincides well with the data of far infrared measurements on the same compound [16].

As can be seen the fits reproduce the main experimental features within one common parameter set for *all* frequencies and at *all* fields [Figs. 1(a) and 1(b)]. They coincide in the smooth step upwards at 35 GHz, the jump downwards at higher frequencies, and the resonantlike structure at 55 and 70 GHz. Moreover, each curve can be optimized individually by a small variation of the parameter set (not shown). The remaining sharp but small resonances of Fig. 2(b) (horizontal arrows) can be fitted with two additional magnetic oscillators, $\tilde{\mu}_{osc}^\eta(\omega)$ and $\tilde{\mu}_{osc}^\theta(\omega)$, for the η and θ excitations, respectively (not shown). The corresponding relaxation frequencies, Γ_μ^η and Γ_μ^θ, are 1 order of magnitude less in size than Γ_ε^η.

Apart from that fact all oscillator relaxation frequencies, Γ_ε^η, Γ_μ^η, and Γ_μ^θ, are extremely small in comparison to relaxation rates of one particle excitations (see, e.g., [17]). This leads to the excitations observed in our measurements demonstrating a strong collective character. Since the condition $\Gamma^{\eta,\theta}_{\epsilon,\mu} < \omega$ is met at least by a factor of 2.3 even at the lowest frequency (35 GHz), the collective excitations do represent propagating modes.

We can summarize that the microwave excitation spectrum of $CeRu_2Si_2$ is completely described by the oscillator functions $\tilde{\epsilon}^{\eta}_{osc}(\omega)$, $\tilde{\mu}^{\eta}_{osc}(\omega)$, and $\tilde{\mu}^{\theta}_{osc}(\omega)$. They correspond to collective modes which become soft at the critical field. This result is surprising since $CeRu_2Si_2$ exhibits *no* long range magnetic order and its thermodynamic properties reveal *no* phase transition at B_c.

An overall synthesis can be given within the Fermi liquid theory of Landau. Following this approach the propagating modes are interpreted as representing an electronic zero sound mode and a spin wave for $B < B_c[\tilde{\epsilon}^{\eta}_{osc}(\omega),\tilde{\mu}^{\eta}_{osc}(\omega)]$ whereas for $B > B_c$ only a spin wave is observed $[\tilde{\mu}^{\theta}_{osc}(\omega)]$. These modes can be regarded as well defined quantities above the hydrodynamic energy scale $(\omega > \Gamma^{\eta,\theta}_{\epsilon,\mu})$. As B moves towards B_c they become soft, for $\omega^{\eta,\theta}_0 \leq \Gamma^{\eta,\theta}_{\epsilon,\mu} = 1/\tau_{hyd}$ they are damped out and a phase transition is prevented.

In this Letter we show that the dynamic character of the electronic Fermi liquid in $CeRu_2Si_2$ can be explained by the propagation of an electronic zero sound mode and spin waves. Further experiments on other heavy fermion compounds are planned.

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