Ultrafast Relaxation Dynamics in Normal Metals and Heavy Fermions

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Ultrafast time-resolved optical spectroscopy reveals the nature of the quasiparticle relaxation dynamics in condensed matter systems. Femtosecond time-resolved pump-probe optical measurements have been widely used for normal metals, conventional and high-T_c superconductors and charge-density wave solids. These experiments show in the time domain how constituent degrees of freedom of materials interact with each other, which is important to understand the physics governing the ground state and the low-energy excited states of materials.

Here we report calculations of the quasiparticle relaxation dynamics in light (normal metals) and heavy fermion materials. We solve the coupled Boltzmann equations for both electrons and phonons, with electron-electron and electron-phonon scattering included [1].

In ultrafast optical pump-probe spectroscopy, an ultrafast laser pulse initially excites the electron system, and the probe pulse monitors the relaxation of the electrons by measuring transient optical properties with subpicosecond time resolution. Usually, the relaxation of the excited electrons is due to the thermalization among electrons and other degrees of freedom, such as phonons.

In Fig. 1 we show the experimental and theoretical results of the relaxation time for the light electron system (normal metal) $LuAgCu_4$. Contrary to the simple two-temperature model (TTM) of coupled electron and phonon heat baths, the experiment and model solution of the coupled Boltzmann equations show saturation at low temperatures.

An interesting question is why does a thermal electron distribution relax slower, $\tau \sim T^{-3}$, than a nonthermal one, which relaxes faster and with a less T-dependent rate at low T. As shown in Fig. 2(a), if the electrons have a thermal distribution at T (solid line), which is slightly higher than the final T (dotted line), the electron-phonon (e-p) scattering important for the relaxation happens within the range T near the Fermi energy. Therefore, the relaxation rate depends on how many phonon modes exist at low T. In contrast, if the electrons do not thermalize [solid line in Fig. 2(b)], then e-p relaxation occurs in the energy range of order of the Debye energy. This makes the e-p relaxation faster and less T-dependent, as is indeed observed in Fig. 1.

The relaxation time for $YbAgCu_4$ differs markedly from the normal metal case, because of one important difference: if the Fermi velocity v_F is slower than the sound velocity v_s, then the phonon integration in the e-p collision integral has a lower bound, which represents the blocking of e-p scattering for low energy phonons. This greatly influences the e-p relaxation and acts like a bottleneck giving rise to divergent behavior at low T. Thus simultaneous momentum and energy conservation prohibit scattering between heavy electrons and phonons. The above blocking mechanism applies only when both initial and final electron states are within the peak of the DOS. Therefore the results of the simulation are very different from light fermions (Fig. 1) and are shown in Fig. 3 as solid circles.

In conclusion, a nonthermal electron distribution in normal metals is responsible for a temperature independent relaxation time at low temperatures, while for heavy fermions the relaxation time diverges because of a thermal electron distribution and the blocking of e-p scattering due to energy and momentum conservation laws.

[1] K.H. Ahn, et al., *Phys. Rev. B* **69**, 045114 (2004).
[2] J. Demsar, et al., *Phys. Rev. Lett.* **91**, 027401 (2003).

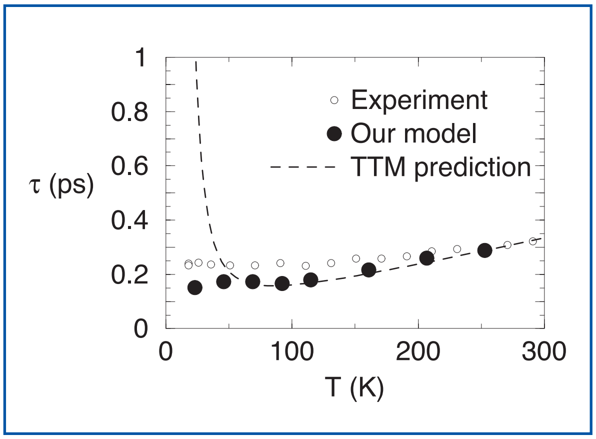

Figure 1*—*
Relaxation time τ calculated from the coupled Boltzmann equations for LuAgCu$_4$ along with experimental data and two-temperature model (TTM) prediction [1].

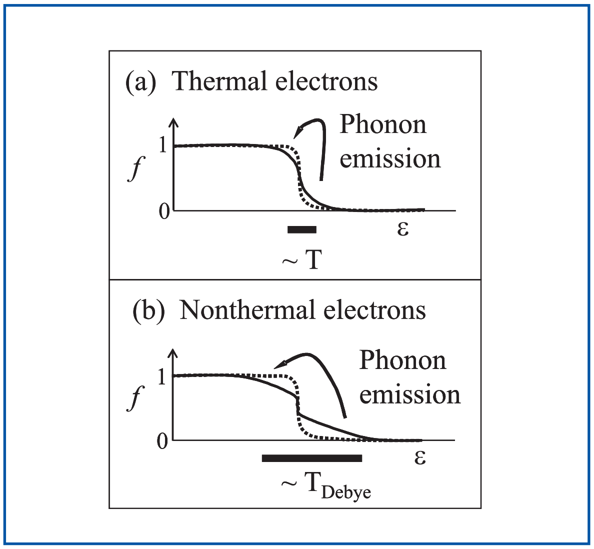

Figure 2*—*
Schematics of relaxation dynamics for (a) thermal and (b) nonthermal electron distributions at low T. Dotted lines represent the final thermal electron distribution.

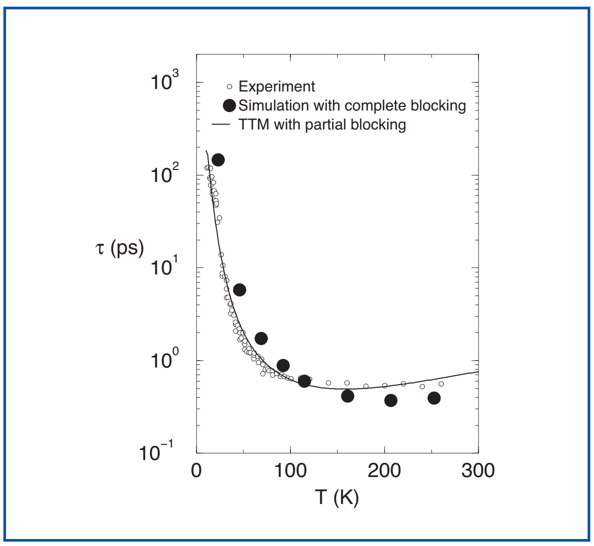

Figure 3*—*
Solid circle: τ calculated for blocking of e-p scattering within peaked DOS due to $v_F < v_s$. Open circle: experimental data for YbAgCu$_4$ [2]. Solid line: results for TTM with partial blocking of e-p scattering within peak.

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