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Dynamics of heavy carriers in the ferromagnetic superconductor UGe_2

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Superconductivity (SC), magnetic ordering and heavy-fermion (HF) behaviour have long been presumed to be in conflict, mainly due to exchange interaction aligning the electron spins in parallel, thereby preventing the pairing, and spin fluctuations in the Kondo effect. However, the possibility of their coexistence is now clearly established in f-electron systems [1]. Remarkably, the heavy quasiparticles (QP) are also responsible for the SC pairing. Furthermore, HF compounds exhibit coupling of SC with ferromagnetism (FM). It is significant that both phenomena seem to be supported by the same heavy QP [2].

In HF, a distinction between localized and itinerant electrons is not always clear [2] – localized states interact with conduction electrons, and thereby affect one another. The unconventional character of electrons exhibiting the two types of behaviour simultaneously is known as a duality problem [3]: spins of *all* local moments participate in the formation of the SC order parameter [4]. A related issue originates from Luttinger's theorem, which states that, in the non- interacting electron band theory, the volume of the Fermi surface (V_{FS}) counts the number of conduction electrons (n_e). For interacting systems this rule changes [5] to manifest a remarkable result that the local spin states (n_{spin}) are also included: $2V_{\mathrm{FS}}/(2\pi)^3 = n_e + n_{\mathrm{spin}}$. Therefore, even though f-electrons are localized as magnetic moments at high temperature, they contribute to the Fermi surface volume in the heavy Fermi liquid – this fundamental point of the HF physics is often discussed in terms of a "small" to a "large" Fermi surface transformation [5]. Both the duality problem and the counting rule considerations require a new conceptual framework. The theory usually considers strongly localized electrons of the f-shell. Here, we examine a different approach focusing on a band with delocalized carriers. The exchange coupling between a carrier and local moments can result in localization into an FM cloud around the electron [6]. The carrier together with oriented neighbouring local moments form a magnetic polaron (MP) [6]. Suppression of spin fluctuations at low temperature promotes coherent MP band transport [6]. When MPs become coherent within the band, the Fermi surface embraces these heavy QP. Formation of an MP band may not only give a natural description of how f-spins gain itinerancy despite being local moments, but may also pave a way to understanding of how Luttinger's theorem works in strongly correlated materials.

μ^+SR spectra in magnetic semiconductors [7] and correlated metals [8–10] allow for interpretation in terms of MPs. Here we apply μ^+SR spectroscopy in high magnetic field to UGe_2. We map the experimental data onto MP model and show that the concept of MP enters naturally the debate on the coexistence of FM order, SC and HF behaviour. At high temperature, a single line is detected in transverse-field μ^+SR spectra of UGe_2. However, below $T \approx 100$ K the spectra change abruptly to reveal a doublet consisting of two distinct peaks. Assuming that the MP state is of the 1s-type with the hyperfine interaction A scaling as R^{-3}, we roughly determine the radius of the electron confinement in the MP as $R \approx 0.25(1)$ nm. The spectra show a noticeable transformation around 80 K (Fig. 1a), suggesting a change in the MP dynamics. We argue that 80 K is a crossover temperature between two types of behaviour: itinerant and static. However, the itinerancy of MPs does not necessarily mean that an MP band is formed at 80 K. On the contrary, transport of MPs just below the crossover temperature is governed by hopping dynamics. Optical studies [11] indicate a suppression of spin flips below T_{C} with a significant increase of the itinerant carrier effective mass. These facts indicate the formation of a spin-

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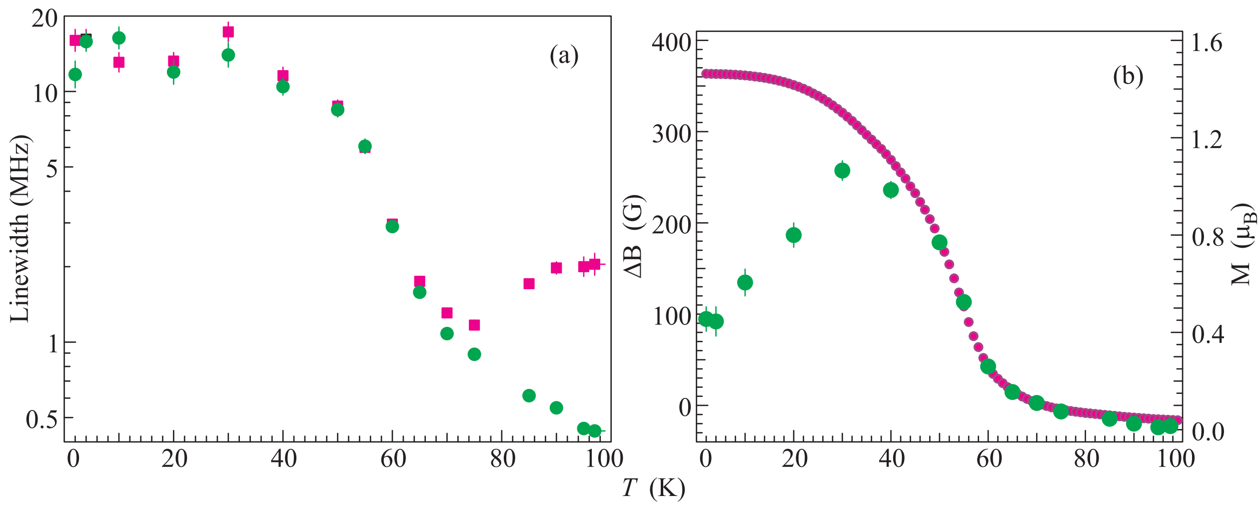

Fig. 1. (Color online) Temperature dependence of parameters of μ^+SR spectra of UGe_2. (a) Linewidths for the doublet: green circles – higher frequency signals, magenta squares – lower frequency signals. (b) – Magnetic field shift detected by the muon (green circles) and bulk magnetization (magenta circles). All data were collected in a magnetic field of 1 T externally applied along the easy axis. The qualitative changes in linewidths occur around 80 K and in ΔB below about 30 K

polarized band composed of heavy carriers. We suggest that this band may be an MP band [6]. Splitting of the two subbands in an FM state ensures coherent transport of MP. Further support for coherent MP band formation comes from the measurements of the local magnetic field shift (ΔB) on the muon (Fig. 1b). At $T^* \approx 30$ K, UGe_2 experiences a crossover between two FM phases.

In summary, our μ^+SR data are set against other properties of UGe_2 recruiting the model of magnetic polarons. Within this model, the MPs become observable when a gap opens up in the spectrum of spin excitations, and undergo a remarkable transition from static behaviour to itinerancy. At low temperature, heavy MPs are proposed to form a narrow band in the vicinity of E_F, profoundly modifying the magnetic, transport, optical and thermodynamic properties of the host. Formation of such a band may explain a number of properties of UGe_2 and other HF materials, including duality of the carriers, interplay between small and large Fermi surfaces, very large anisotropic magnetoresistance, reconstruction of the Fermi surface at T^* and the origin of transition between the two ferromagnetic phases. In particular, our studies support the concept of $5f$-electron itinerancy in UGe_2.

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