# Magnetic resonance in $Ce(Cu_{1-x}Ni_x)_2Ge_2$ and $CeCu_2(Si_{1-y}Ge_y)_2$

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## Abstract

The quasi-ternary heavy-fermion systems $Ce(Cu_{1-x}Ni_x)_2Ge_2$ and $CeCu_2(Si_{1-y}Ge_y)_2$ are investigated by means of magnetic resonance. Starting with the common $CeCu_2Ge_2$ both systems exhibit an alloying-induced transition from antiferromagnetic order to a coherent Fermi-liquid behavior in $CeNi_2Ge_2$ and $CeCu_2Si_2$, respectively.

In heavy-fermion systems the hybridization strength $g = JN(E_F)$ between the local f-moments and the conduction electrons is responsible for the rich variety of different ground states. For both mixed systems $Ce(Cu_{1-x}Ni_x)_2Ge_2$ and $CeCu_2(Si_{1-y}Ge_y)_2$ this hybridization is fine-tuned by alloying, and it is observed that an increasing hybridization changes the character of the magnetic phase transition from antiferromagnetism of the localized 4f-moments to band-type magnetism of the heavy quasi-particles until the magnetic order is totally suppressed [1,2]. The analysis of $^{63}Cu$ NMR and $Gd^{3+}$ ESR ($\leqslant 2\%$ Gd at Ce site) spectra and spin-lattice relaxation of the respective probes at different crystallographic sites reveals these phase transitions.

Fig. 1 shows the temperature dependence of the $^{63}Cu$ spin-lattice relaxation rate $1/T_1$ in $Ce(Cu_{1-x}Ni_x)_2Ge_2$. For $T \geqslant T_N$ and increasing temperatures the relaxation rates for the concentrations $x = 0$ and $x = 0.5$ weakly decrease as it is expected for dominating RKKY-type interactions (Fig. 1(a)). Increasing compensation of the ordered moment with increasing $x$ yields the formation of delocalized band states, and it is observed that the magnetic phase transition is deeply shifted into the Kondo-compensated regime (Fig. 1(b) and (c)). In this regime $1/T_1$ decreases towards low temperatures below the characteristic temperature $T^*$ which is roughly estimated from the maximum of $1/T_1$ at about 20 K. The sharp enhancement of $1/T_1$ due to fluctuations close to $T_N$ possibly is suppressed due to chemical disorder. The solid lines in Fig. 1(b) and (c) indicate the temperature dependence for $1/T_1$ as it is predicted for spin fluctuations in weak itinerant antiferromagnets [3]. This behavior of increasing relaxation rates $1/T_1$ for increasing temperatures within the temperature region $T_N < T < T^*$ corroborates the experimental evidence of heavy-fermion band magnetism found for $x = 0.6$ and $x = 0.7$ [4]. In Fig. 1(d) the spin-lattice relaxation rate for $x = 0.8$ is shown in a semilogarithmic representation and reveals a logarithmic dependence over one decade in the temperature. The coincidence of the magnetic phase transition near zero temperature and the logarithmically diverging specific heat in the relevant temperature region (see inset of Fig. 1(d)) of the concentration $x = 0.8$ suggest that $1/T_1 \propto \log(T/T^*)$ is indicative for a non-Fermi-liquid behavior in $Ce(Cu_{0.2}Ni_{0.8})_2Ge_2$.

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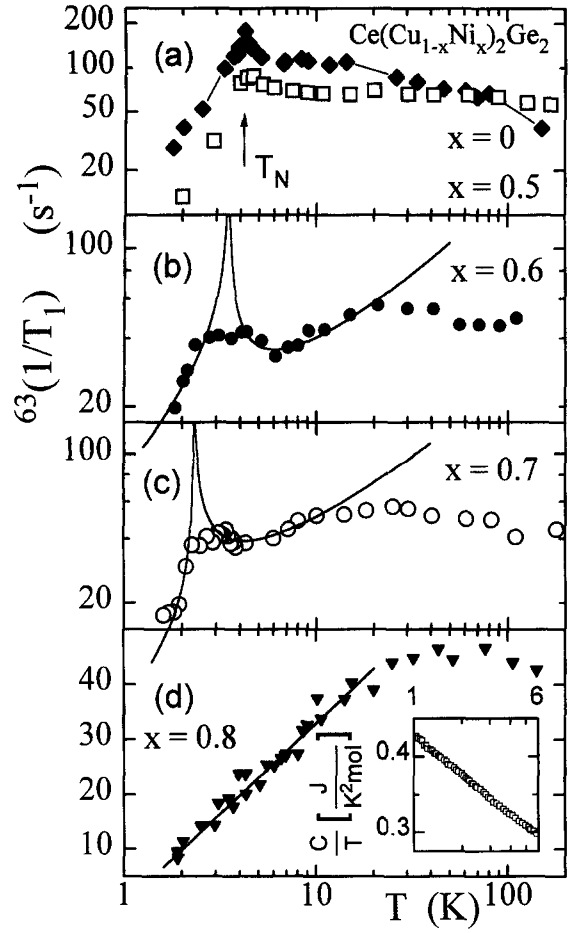

Fig. 1. (a)–(c) Spin-lattice relaxation rate $^{63}(1/T_1)$ versus temperature $T$ in $Ce(Cu_{1-x}Ni_x)_2Ge_2$ on logarithmic scale; (d) semilogarithmic scale for $x = 0.8$. The specific-heat measurements are taken from Ref. [7] (see text).

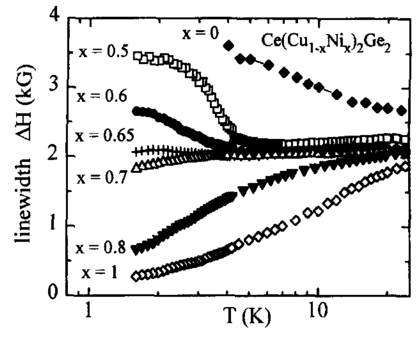

Fig. 2. Temperature dependence of the ESR line width (direction of best exchange narrowing) in $Ce(Cu_{1-x}Ni_x)_2Ge_2$.

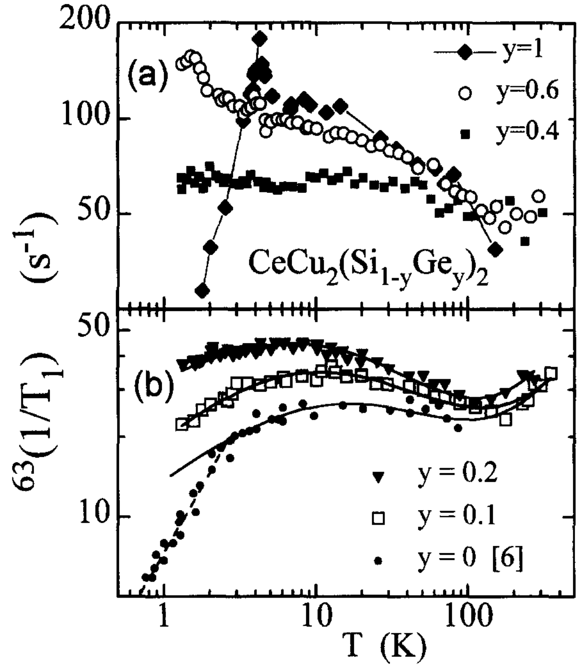

Fig. 3. (a) Spin-lattice relaxation rate $^{63}(1/T_1)$ versus temperature $T$ in $CeCu_2$ $(Si_{1-y}Ge_y)_2$. (b) Solid lines are fits to $T_1^{-1} \propto k_B T \chi_0 / \Gamma + KT$ (see Ref. [4]).

The NMR results of the copper nuclei in $Ce(Cu_{1-x}Ni_x)_2Ge_2$ resemble the ESR measurements of $Gd^{3+}$ relaxation rates obtained from the line width $\Delta H$. In Fig. 2 the ESR line width $\Delta H$ is presented as a function of temperature. For concentrations $x < 0.8$ the magnetism dominates the observed temperature dependence of $\Delta H$: Below $T_N$ the ESR spectra show a strong inhomogeneous broadening caused by local field inhomogeneities within the ordered state. The nonmagnetic samples $x = 0.8$ and $x = 1$ clearly exhibit a different curvature in $\Delta H(T)$ for temperatures below $T^*$: For $x = 0.8$ the line width reveals a convex curvature yielding a logarithmic temperature dependence for $T < 5$ K comparable to the NMR results (Fig. 1(d)), whereas for $x = 1$ a concave curvature is observed due to a linear Korringa relation for the Fermi-liquid regime below $T \approx 10$ K (see Ref. [5] for $CeCu_2Si_2$).

The consequence of increasing hybridization on the temperature dependence of $1/T_1$ for $CeCu_2(Si_{1-y}Ge_y)_2$ is shown in Fig. 3. A sharp decrease of $1/T_1$ below $T_N$ due to the opening of a gap in the magnetic exitation spectrum is observed for $y = 0$ only. For $y = 0.6$ a second phase transition below $T_N \approx 2$ K appears according to results of resistivity and susceptibility measurements [2]. The enhancement of the spin-lattice relaxation rate due to RKKY-type interactions strongly weakens for germanium concentrations $y \leqslant 0.4$ and a Korringa-type relaxation of conduction electrons occurs for very high temperatures. For temperatures $T \geqslant 1.3$ K no signature of a magnetic phase transition is detected for small germanium concentrations $y \leqslant 0.2$ (Fig. 3(b)). This behavior gives clear evidence for stronger Kondo-type interaction as it is observed for $Ce(Cu_{1-x}Ni_x)_2Ge_2$ (Fig. 1(b) and (c)) and therefore it allows to apply simplified model calculations which take into account the most prominent and important interactions with respect to the nuclear relaxation [4]. These calculations are presented as solid lines in Fig. 3(b) revealing a power-law dependence of the quasi-elastic line width $\Gamma_{\mathrm{NMR}} \propto T^{0.7}$ for $y = 0.2$ and $\Gamma_{\mathrm{NMR}} \propto T^{0.6}$ for $y = 0.1$, $y = 0$. The dashed line reflects the Korringa relation $(T_1T)^{-1} = 7.35\,(\mathrm{s\,K})^{-1}$ for the Fermi-liquid regime of $CeCu_2Si_2$ found by Asayama et al. [6]. Detailed investigations for sample concentrations $y < 0.1$ to lowest temperatures are highly desirable in order to elucidate the interplay of residual magnetic correlations and pure Fermi-liquid behavior with respect to the heavy-fermion superconductivity of $CeCu_2Si_2$ below $T_C \approx 0.7$ K.

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