"Electronic bottleneck effect" in Cu:Er system

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(Submitted August 12, 1974)
ZhETF Pis. Red. 20, No. 6, 416–419 (September 20, 1974)

An "electronic bottleneck effect" of two spin subsystems coupled by exchange interaction (conduction electrons and localized magnetic moments), with significantly different g factors, was observed in single crystals of copper doped with paramagnetic erbium.

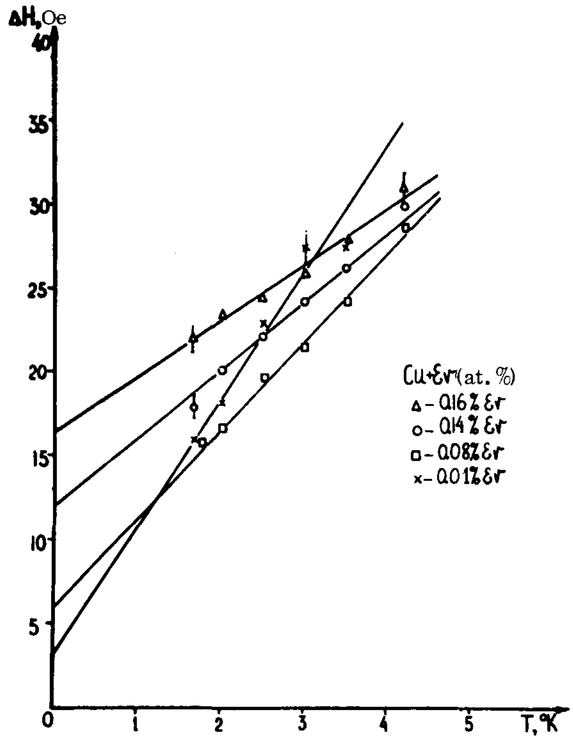
It is well known that in metals the presence of strong exchange interaction between the conduction electrons (CE) and the localized magnetic states (LMS) with close values of the g-factor leads, with increasing paramagnetic-impurity concentration, to the phenomenon of the "electronic bottleneck" (EBN).[1,2] This phenomenon consists, in particular, of the vanishing of the exchange-governed relaxation contribution to the line width ΔH of electron paramagnetic resonance (EPR) on the localized magnetic states, a fact experimentally reflected in a characteristic dependence of ΔH on the concentration C.

In the case of spin subsystems with strongly differing g, the situation changes significantly. It was shown (see, e.g., [3]) that the EBN phenomenon is possible also in the case when the condition

$$\omega_s - \omega_e << \frac{1}{T_{es}} + \frac{1}{T_{se}} \quad (1)$$

is satisfied, where T_{es} and T_{se} are the times of relaxation of the CE spin system into the LMS spin system (relaxation times of the Overhauser and Korringa type), ω_s and ω_e are the resonant frequencies of the LMS and CE, $\omega = g\beta H/\hbar$, β is the Bohr magneton, and H is the constant magnetic field. We report here preliminary data on the first observation of the EBN in such systems, using Cu : Er as an example (the g-factor is $g_e \approx 2.03$ for the CE of pure copper[4] and $g_s \approx 6.77$ for the free erbium ion[5]) and propose for the results an interpretation based on a simple thermodynamic approach. It has turned out that the condition (1) is actually unnecessary.

Measurements by the EPR method at 9300 MHz in the temperature range 1.6–4.2 °K were performed on single crystals of pure copper doped with erbium impurities with concentrations 0.16, 0.14, 0.08, and 0.01 at.%. The observed spectrum of the EPR on the localized magnetic moments of erbium consisted of a central line with $g = 6.84 \pm 0.02$ (the g-factor was independent of C within the limits of experimental error) and six hyperfine-structure lines due to the odd isotope Er^{167} with a constant $A = 74.8 \pm 1.5$ Oe. The figure shows the temperature dependence of the width of the central line



Temperature dependence of EPR line width for the investigated samples.

for the investigated samples. A variation of the temperature slope of the curves with changing concentration is clearly evident, $\partial\Delta H/\partial T$ inversely proportional to c. Such a behavior of $\Delta H(T, c)$ is typical of the EBN. At the same time, an estimate of the Korringa relaxation rates (from measurement data for the sample with $c = 0.01$ at. %, for which there is still no EBN) and the Overhauser relaxation rate (for the sample with $c = 0.16$ at. %) yielded 4×10^8 and 8×10^9 sec^{-1}, respectively. This shows that relation (1) is not satisfied in our case and thus, the rate of exchange between the spin subsystems is clearly less than the difference between the natural frequencies. At relatively long CE spin-lattice relaxation times T_{eL}, however, it becomes necessary to take into account the finite specific heat of the spin system of the EC, which leads to the EBN also when (1) is violated. We introduce the "bottleneck" parameter $\sigma = C_s T_{es}/C_e T_{se}$, where C_s and C_e are the specific heats of the LMS and the CE subsystems. At $\sigma > 1$ (an estimate yields $\sigma \approx 3$ in our case), in full analogy with the "phonon bottleneck" phemonenon in dielectrics, [6] we obtain for the effective rate of the spin relaxation of the LMS to the lattice

$$\frac{1}{T_{eff}} = \frac{3\eta(E_F)kT}{2S(S+1)C}\frac{1}{T_{eL}}, \qquad (2)$$

where $\eta(E_F)$ is the state density on the Fermi surface and S is the effective spin. In the derivation of this relation we took into account the fact that only a fraction of the LMS energy, equal to $g_e\beta H$, is transferred to the lattice via the CE spin system. It is interesting that (2) coincided with the known expression of Hasegawa. [1] If it is assumed that (2) describes the change of the temperature-dependent contribution to ΔH with increasing C (the temperature-independent contribution is connected principally with dipole-dipole interaction), then we can carry out an additional experimental verification of the presence of the EBN effect. [2] To this end, nickel at concentrations ~0.1 and 0.5 at. % was introduced into the sample with Er concentration $c = 0.14$ at. %. The introduction of an additional scatter shortened T_{eL} and led in accordance with (2) to an increase of $\partial\Delta H/\partial T$. With the aid of (2) we obtain $T_{eL} \approx 10^{10}$ sec^{-1}, and for the Ni impurity in Cu we have $\partial(1/T_{eL})/\partial c \approx 5\times10^9$ (sec at. %)$^{-1}$.

We note in conclusion that the peculiarity of the EBN effect in our case consists in the fact that, together with the characteristic $\Delta H(T, c)$ dependence, there are observed also an "electronic Knight shift" for the g-factor and a hyperfine structure.

The authors are deeply grateful to S.A. Al'tshuler and to B.I. Kochelaev for useful discussions.

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