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# Size-effect of Kondo scattering by Fe impurities in Cu point contacts

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The low temperature $dV/dI(V)$ characteristics are investigated for point contacts of various sizes ($d \sim$ 2–35 nm) using a mechanically controlled breakjunction of a Kondo alloy CuFe (0.1 at.%). A size effect, being manifested in an increase in the effective Kondo temperature with decreasing contact size, is found both on voltage and magnetic field $dV/dI$ dependences. In accordance with the prediction of the Zarand-Udvardi theory the enhancement of the Kondo temperature in the CuFe alloy appears to be quantitatively much smaller than in CuMn alloy of the same concentration. This enhancement is due to the strong fluctuations of the local electron density of states in the ultrasmall metallic contacts. The Kondo temperature of a magnetic impurity provides a *local probe* of these fluctuations.

## Introduction

Recent developments in producing $3D$ metallic point contacts by the mechanically controllable breakjunction technique [1] have opened a new opportunity for a detailed study of the size dependences of a number of physical properties of metals, such as conductance quantization [2], superconductivity of weak links [3], and magnetic impurity scattering (Kondo effect) [4], in the range of sizes previously inaccessible, namely from several tens of nm down to the one-atom scale.

Unexpectedly, in view of previous measurements of size effects in the low-dimensional CuFe, AuFe, and CuCr Kondo alloys [5–7], it was found that the Kondo scattering in CuMn and AuMn point contacts increases with decreasing contact size, which is seen as a huge increase in the effective Kondo temperature [4,8]. This results in the following three features, which are anomalous with respect to the quasi-classical perturbation theory [9]. These features are observed in the low temperature differential resistance versus voltage characteristics. The first feature is a weaker dependence of the relative zero-bias Kondo peak intensity on the contact size, compared with that for the phonon structure. The second manifests itself through a noticeable broadening of the Kondo maximum for ultrasmall contacts, showing explicitly that a larger energy scale (or, equivalently, Kondo temperature) is involved. Finally, the third concerns the magnetic field behavior of the zero-bias Kondo peak. While for contacts larger than about several tens of nanometer the expected Zeeman splitting is nicely seen [4,8], it disappears for contact sizes smaller than 10 nm, illustrating the more robust screening of the impurity magnetic moment.

Recently an explanation of the experimental phenomena was proposed in terms of the strong electron local density of states (LDOS) fluctuations in the constriction region [10]. The key idea is that the electron LDOS $\rho_0(\mathbf{r})$ at the Fermi energy is increased at some points $\mathbf{r}$ in the contact due to the constructive interference of electron wave functions reflected by the contact boundaries (quantum size effect). Since the Kondo temperature exponentially depends on $\rho_0$,

$$T_K = T_F \exp\left(-1/J\rho_0\right), \qquad (1)$$

a relatively small increase in $\rho_0$ may lead to large increase in Kondo temperature provided the exchange constant $J$ is small enough, as it is the case for a Mn impurity in noble metals. On the other hand, the larger is the parameter $J$ the smaller is the $T_K$ enhancement effect. Hence, for Fe impurity in noble metals with the $J$ parameter approximately twice as large, the effect should be noticeably smaller. In fact, previous experimental estimates of the Kondo temperature in point contacts [11,12] for iron impurities yielded numbers quite compatible with the bulk value, unlike those for manganese [11].

Since with the pressed-type technique the size dependence of Kondo scattering in point contacts could not be studied due to the unwanted doping of the contact region with uncontrolled impurities and low stability of small size contacts, we decided to apply the mechanically controllable breakjunction technique for this purpose. Stimulated by the predictions of the Zarand-Udvardi theory [10] and wishing to compare the results with our previous measurements on CuMn alloys [4,8], we undertook a detailed study of the size dependence of Kondo scattering by Fe impurities in Cu point contacts. Here we have found only a very small size dependence of the Kondo effect in contacts with sizes down to 1.5 nm, in qualitative agreement with the theoretical predictions. A small increase in effective Kondo temperature was observed, both in the voltage and magnetic field dependences of Kondo scattering, by decreasing the contact size. Unfortunately, a quantitative comparison cannot be made yet, due to the lack of the corresponding quantum theory.

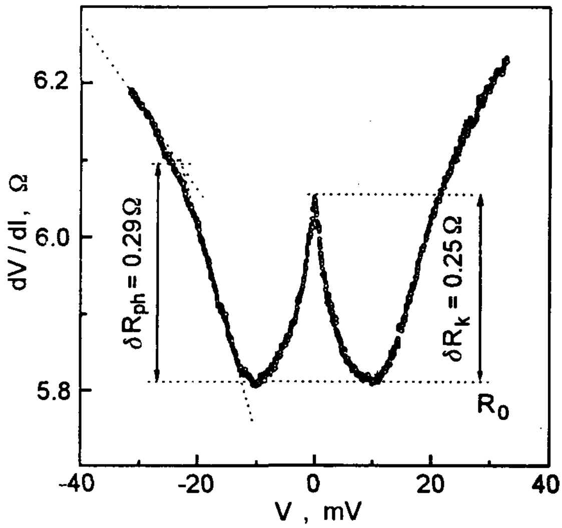


*Fig. 1.* Differential resistance $dV/dI$ as a function of voltage bias recorded for a CuFe (0.1 at.%) junction with $R_0 = 5.8\ \Omega$ ($d$ = 14.6 nm) and $T$ = 0.5 K, $H$ = 0.

## Experimental details

Two samples in the shape of wires with 0.2 mm diameters were prepared from Cu alloys with 0.10 at.% of Fe. Note that this alloy has nominally the same impurity concentration as the CuMn alloy which we have systematically studied before.

As in our previous study, we used the mechanically controlled breakjunction technique to produce point contacts (PC) of adjustable size. A piece of wire of about 2 cm length is used in the experiment. After cutting a notch in the center of the samples they are annealed at 400–500 °C for 4–5 h. The notched and annealed pieces of alloy are then glued with Staycast epoxy to the phosphor-bronze substrate and voltage and current leads are attached. The substrate can be bent inside the cryostat by means of mechanical and piezo drives, and the specimen is broken at the notch in ultrahigh vacuum, insured by the liquid helium environment. After the break the freshly exposed surfaces can be pushed in touch again, and stable contacts with different sizes can be easily achieved.

The contact size $d$ is estimated from the equation

$$d\left[R_0 d - \beta(\nu)\rho_m\right] = 16(\rho l)/3\pi \qquad (2)$$

following from the Wexler formula [13]. Here $R_0$ is the zero-bias contact resistance which we take equal to the minimum value of the even part of the differential resistance (Fig. 1); $\beta(\nu)$ = 0.7–1.0 is the slowly varying function of the mean free path to contact diameter ratio. The $\beta$ value for our particular case is $\approx$ 0.7, and $\rho_m$ is the magnetic part of the total bulk resistivity $\rho$ ($\rho_m$ = = 1,21 $\mu\Omega\cdot$cm for CuFe (0.1 at.%) alloy [14]). For the $\rho l$ product we use the free electron value for Cu $0.653\cdot 10^{-11}\ \Omega\cdot$cm. Since the bulk mean free path due to magnetic scattering is comparable with our larger contacts, the above corrections to the Sharvin formula are necessary.

Similar to the CuMn alloys [4], we define the relative intensities of the Kondo peak, $\delta R_K/R_0$, and the increase in differential resistance due to phonon scattering, $\delta R_{ph}/R_0$, as shown in Fig. 1. The steep rise of $dV/dI(V)$ at the characteristic Cu-phonons energies 15–20 meV [13] evidences that we are in the spectroscopic regime of charge transport through the point contact. In this regime, at any point around the contact, the distribution function of conduction electrons in the momentum space consists of two parts with sharp boundaries between the filled and (partially) empty states shifted in energy with respect to each other by an applied voltage $eV$. For some contacts, we have estimated the maximum value of the electron-phonon interaction function $g_{PC}(eV)$ using the formula

$$g_{PC}(eV) = \left(12.9/\sqrt{R_0}\right)\, dR/dV \qquad (3)$$

(where $[R, R_0] = \Omega$; $[V]$ = mV, $g_{PC}$ is dimensionless), which follows from expressions (6) and (9) of Ref. 13. This value appears to be of the order of 0.2 for contacts with sizes smaller than about 10 nm. This means that for this range of sizes the regime of the current flow is ballistic, becoming intermediate between the ballistic and diffusive for larger contacts. We find independent evidence for this in the 0.5 value for the exponent in the size dependence of the relative phonon intensities (see below). Such a dependence is intermediate between $\delta R_{ph}/R_0 \propto d$, and $\delta R_{ph}/R_0 \approx$ $\approx$ const, characteristic for pure ballistic and diffusive regimes, respectively.

Since the Kondo effect is expected to be an even function of the bias voltage we extracted the even part of the point-contact spectra according to the standard formula

$$R_{\text{even}} \equiv \tfrac{1}{2}\left[R(V) + R(-V)\right], \qquad (4)$$

where $R = dV/dI$. Usually the odd part of the spectrum is much smaller than the even one, and is probably due to the asymmetric distribution of impurities around the contact leading to a nonzero thermopower. To compare the Kondo-scattering contributions for contacts with different sizes we subtract the $R_0$ value from the spectra, and normalize them by the maximum $\delta R_K$ at zero bias.

The resolution of point-contact spectroscopy is determined by the temperature $T$ and modulation voltage amplitude, $v_{1,0}$, through the formula [15]

$$\sqrt{(3.53k_BT)^2 + (1.73v_{1,0})^2} \qquad (5)$$

for the first derivative of the $I$-$V$ characteristic. Since in our experiments the temperature was about 0.5 K and modulation voltage did not exceed 40–50 $\mu$V, the resolution was better than 0.17 meV.

The superconducting solenoid can supply a magnetic field up to 12 T oriented nominally parallel to the contact axes. This field created a force acting on the point contact electrodes that often lead to small random changes of the contact resistance (usually less than 10% of $R_0$). Since one should not expect any influence of field on the high voltage bias branches of PC spectrum, we found that scaling of the $dV/dI$ curves by the ratio $R_0(0)/R_0(H)$ could reproduce the high voltage background of the zero-field curve better than the corresponding $R_0$-offset (Fig. 2). Thus, while studying the magnetic field dependences, we first scaled all the curves in such a way that they all had a background common with the zero-field curve. An example of this scaling procedure is shown in Fig. 3. Note that our conclusions do not depend on the procedure chosen, and are qualitatively the same even if we use only $R_0$-offsets to match the $R(V)$ curves taken at different fields.

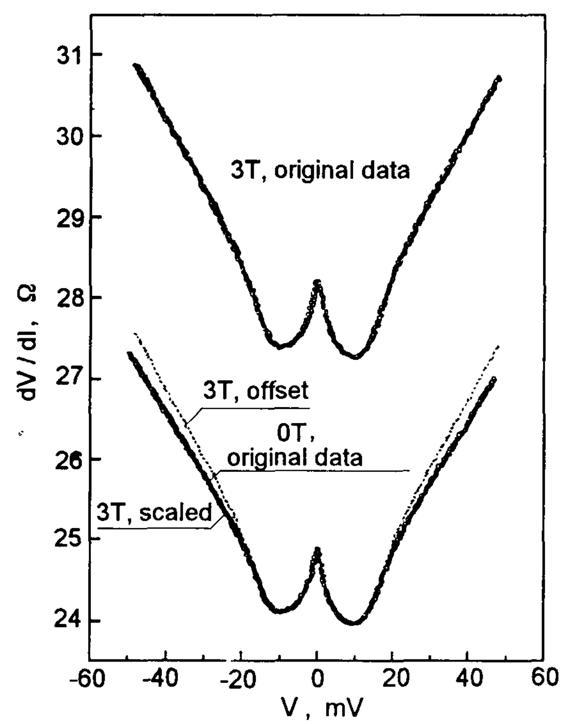


*Fig. 2.* A typical example of reducing the original data shifted by magnetic field to match with the zero-field curve. It is demonstrated that the scaled curve fits better that the offset one. The CuFe (0.1 at.%) junction with $R_0 = 24\ \Omega$ ($d = 7$ nm).

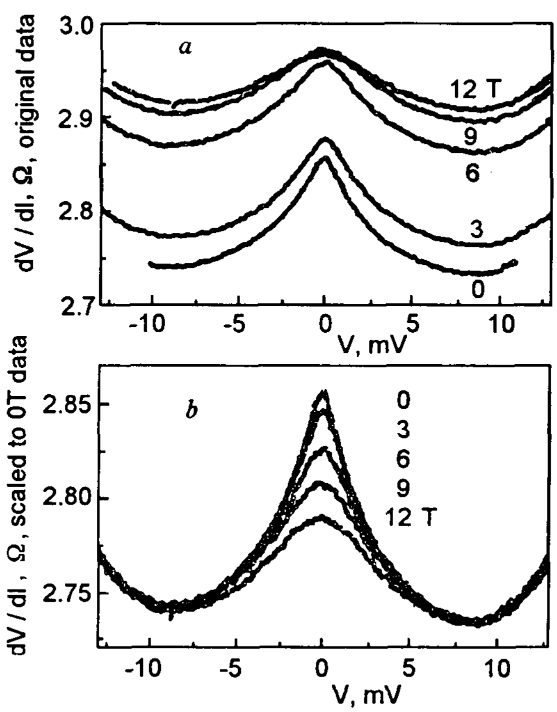


*Fig. 3.* The magnetic field dependence of the Kondo peak for CuFe (0.1 at.%) contact with $R_0 = 2.74\ \Omega$ (*a*). The curves are the same as in (*a*) but scaled along the $R$ axis to match the background for $|V| > 8$ mV of the zero-field curve (*b*).

## Results

In Fig. 4 the low-bias part of the point contact spectra are shown as measured, only the background approximated by a straight line connecting the two $dV/dI$ minima is subtracted. These curves should be compared with Fig. 2 in Ref. 4 for the CuMn alloy plotted in the same way. A clear difference in the size dependencies of the peak widths is revealed. Unlike the noticeable increase in the Kondo-peak width with decreasing contact size observed for CuMn, the CuFe Kondo peaks preserves essentially the same shape in the whole range of contact resistances studied*. This can be even more dramatically demonstrated by com-

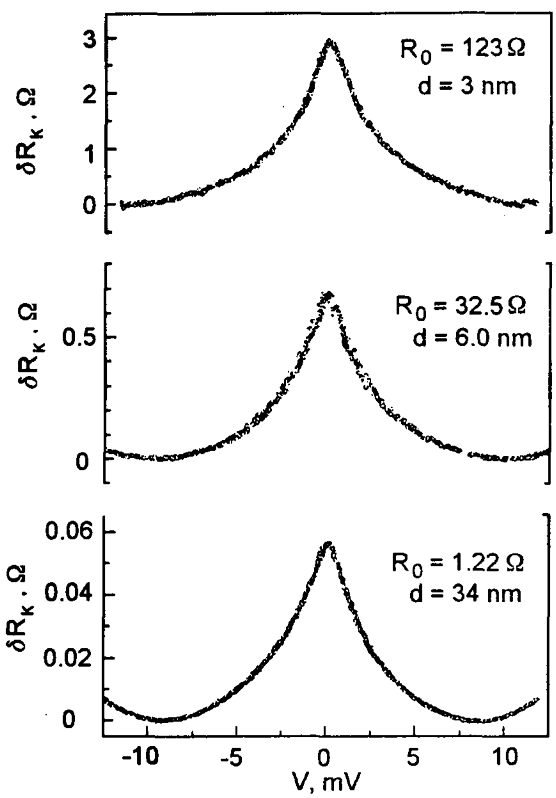


*Fig. 4.* The Kondo maximum in the differential resistance for point contacts of CuFe (0.1 at.%) with resistances $R_0$ between 1.22 Ω and 123 Ω.

paring the normalized even parts of the spectra for CuMn and CuFe on a semilogarithmic scale (Fig. 5). Here all the CuFe spectra for resistances from 1 Ω to several hundreds of Ohms converge essentially into a single curve, only very slight systematic shifts to higher energies can be noticed for the smallest of the contacts (Fig. *5,b*). The 123 Ω curve goes against this trend demonstrating the fluctuations in the impurity position inside the constriction region. Comparison between the CuMn (0.1 at.%) spectra for samples cited in Fig. 2 of Ref. 4 and derived in the same manner show clear increases of the energy scale determined by the Kondo temperature for large resistances (Fig. *5,a*).

The low voltage parts of the Kondo scattering peaks in PC spectra are shown in Fig. 6. Note that there are no obvious quadratic dependences down to the voltages of the order of a few tenths of mV. The curvature of PC spectra is always positive, except for the small portions near zero bias which, most probably, are due to the resolution limitations. This corresponds to the resistivity measurements on bulk CuFe alloys [16], where a quadratic temperature dependence was seen only at $T \ll 1$ K. which is equivalent to $V \ll 0.3$ mV in our case as we discuss below.

In Fig. 6 small but definite shifts to higher biases are seen for contacts with decreasing sizes. To make the point clearer we also show the smooth polynomial fits to the experimental data, shifted by 0.1 along the $R$ axis for clarity. We believe the size effect seen in the voltage dependences of these relatively large contacts, though small, is less random than for smaller diameter contacts of Fig. *5,b* due to smaller fluctuations of relative impurity number in the larger effective contact volume. For future use we plot in Fig. 6 spectra for those contacts which are most extensively studied in magnetic fields. Also the voltage scale is chosen to correspond to the field intensity range in our experiments (see below).

Unlike that of the CuMn alloys the intensity of the Kondo peak for the CuFe alloys, relative to the phonon structure, remains constant over the whole range of contact sizes. This is demonstrated in Fig. 7 where the exponents for relative intensities are the same for Kondo and phonon structures. The anomalous increase in the relative intensity of impurity scattering that was observed for CuMn, is not seen down to

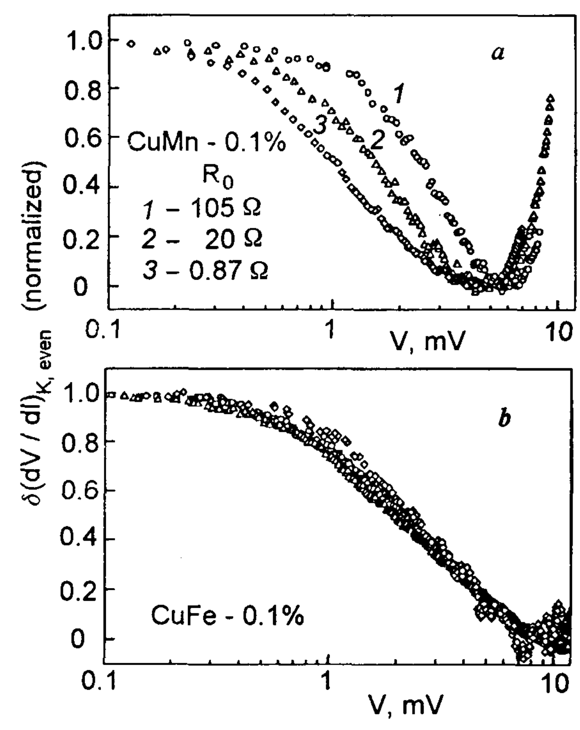


*Fig. 5.* The normalized even parts of Kondo maximum for CuMn (0.1 at. %). These data are taken from Fig. 2 of Ref. 4 (*a*). Similar curves recorded for CuFe (0.1 at.%) with resistances (diameters): 1.22 Ω (33.8 nm); 17.4 Ω (8.23 nm); 123 Ω (3.0 nm), and 417 Ω (1.6 nm) (*b*).

* The difference in shape for biases $|V| \geq 7.5$ mV is due to more smeared phonon $R(V)$-structure centered at $V = 15$–$20$ mV for low resistance contacts, which is apparent already at biases of about 7.5 mV.

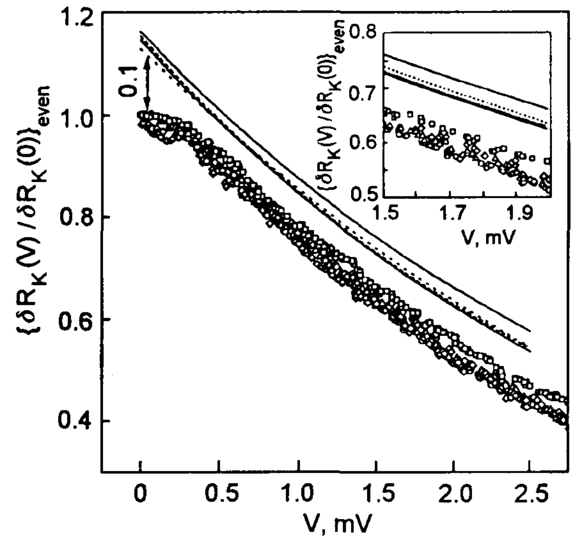


*Fig. 6.* The low-voltage bias parts of the Kondo peaks for the CuFe (0.1 at.%) contacts on which the magnetic field measurements were carried out (Fig. 9). The resistances (sizes) are 0.975 Ω (38.4 nm); 2.74 Ω (21.7 nm); 8.65 Ω (11.8 nm); and 27.4 Ω (6.5 nm). The lines show the 4th power polynomial fits to the experimental data shifted along the $R$ axis for clarity. The inset shows the results on an enlarged scale.

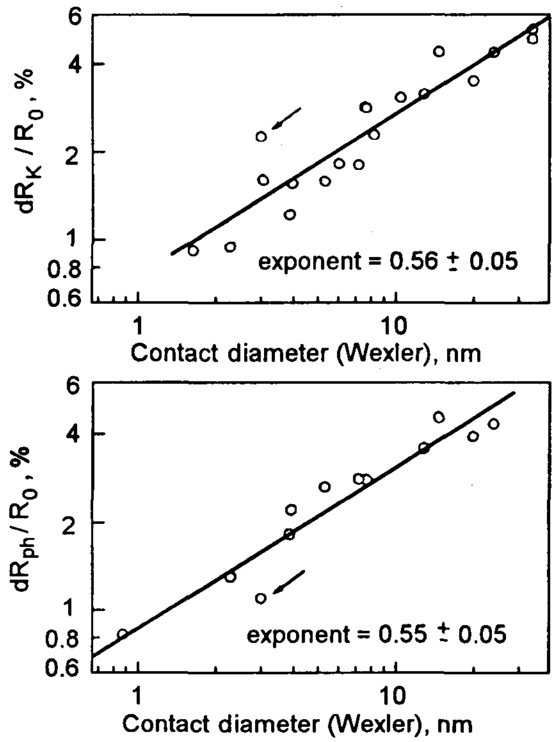


*Fig. 7.* The relative magnitudes of the Kondo and phonon structures as a function of the contact diameter for the CuFe (0.1 at.%). The way of determining $\delta R_K$ and $\delta R_{ph}$ is shown in Fig. 1.

contact sizes corresponding to the average interimpurity distance $r_0 = 2.27$ nm calculated for 0.1 at.% Fe concentration. Due to the contact instability and the current source limitations, we were unable to measure both the Kondo and phonon structures for all contacts. Interestingly, that contact which has an anomalously high intensity of Kondo structure has an anomalously low intensity of phonon structure (see dots marked by arrows in Fig. 7). This is expected since reducing the electron mean free path by impurities would reduce the phonon structure intensity [17]. Also, one can notice the absence of a Kondo peak intensity data point for the smallest of our contacts ($d = 0.8$ nm). We discarded this point since it lay far below the extrapolated $d$ dependence. Here the size of this contact is several times smaller than the average interimpurity distance $r_0$, and the $\delta R_K/R_0$ value is too low, probably due to an impurity location somewhere at the periphery of the contact.

In Fig. 8 the Kondo peak is shown for the contact of $R_0 = 2.74\ \Omega$ ($d = 21.7$ nm), measured in magnetic fields up to 12 T. Similar measurements were carried out for several other contacts with different resistances in order to investigate the size dependence of the magnetic field behavior of the Kondo scattering. The even parts of $dV/dI$ characteristics, scaled to the zero field spectrum as described above, were plotted normalized to the zero-bias Kondo peak at $H = 0$. Unlike for the CuMn contacts of about the same size, there is no Zeeman splitting of Kondo maxima by the magnetic field, since the bulk Kondo temperature for Fe impurity in Cu ($T_K \simeq 30$ K) is significantly larger than the temperature of our measurements, and the impurity magnetic moment is effectively screened by conduction electrons. Nevertheless, the magnetic field strongly suppresses the intensity of the Kondo peak acting in a fashion analogous to raising the temperature or voltage bias [18].

To compare the magnetic field suppression of the Kondo peak in contacts of different sizes we plot in Fig. 9 the normalized intensities of zero-bias Kondo maximum, as a function of field for contacts with

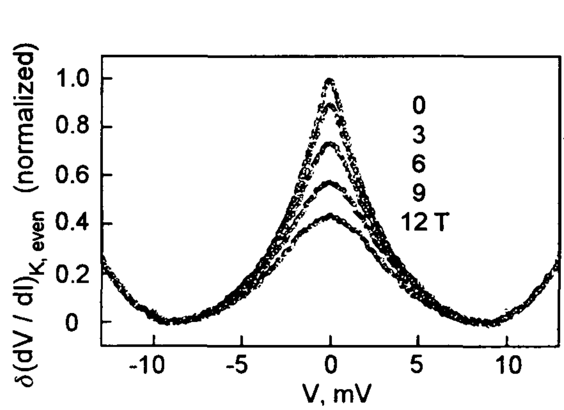


*Fig. 8.* The magnetic field dependence of the normalized even parts of the Kondo structure for the CuFe (0.1 at.%) contact with $R_0 = 2.74\ \Omega$ ($d = 21.7$ nm) from Fig. 3.

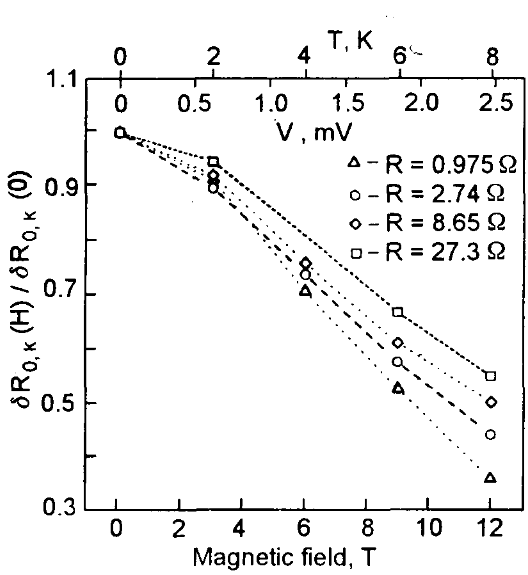


*Fig. 9.* The suppression of the Kondo peak by an external magnetic field for point contacts of various resistances (sizes). The voltage dependences for the same contacts are shown in Fig. 6. For an explanation of the upper horizontal scales see text.

resistances differing more than an order of magnitude, corresponding to a 6-fold change in the contact size. Unfortunately, contacts with smaller sizes become unstable in high magnetic field and this hinders the measurements. Together with voltage bias dependences presented in Figs. 5 and 6, Fig. 9 represents the central result of our work: *although the size dependence of the Kondo scattering in* CuFe *alloys is considerably smaller than in* CuMn *alloys, a weak size dependence is still clearly observed.* The smaller the contact the less is the magnetic field suppression of Kondo peak, which can be qualitatively interpreted as the result of a corresponding increase in the effective Kondo temperature. We will discuss this property in greater details in the next section.

## Discussion

A comparison of our experimental results with the theoretical predictions is not a simple task, since the perturbation approach breaks down for temperatures and energies comparable and smaller than the Kondo temperature which is quite high in case of CuFe alloys. There is no rigorous theory for transport properties of Kondo alloys in our energy range of interest. The approximations do not fully describe the temperature dependence of the bulk resistivity at temperatures around and below $T_K$ [18]. The best we can do for temperatures below the Kondo temperature is to use the empirical relation [6,18]

$$\rho_m = A - B \ln \left[1 + (T/\theta)^2\right] , \qquad (6)$$

where $\ln(\theta/T_K) = -\pi[S(S+1)]^{1/2}$, $S$ being the impurity spin, which for the case of Fe should be taken equal to 1/2 and leads to the relation $\theta \simeq 0.006 T_K$.

To compare the temperature dependence of bulk resistivity and the voltage dependence of point contact resistance, one has to know the coefficient $\alpha$ in the relation $eV = \alpha k_B T$. Since the Kondo effect depends on the complete energy distribution function for conduction electrons, and the theory for its modification, in case of the specific nonequilibrium distribution function for electrons in a point contact, is not yet available, we adopt a simplified approach by taking the relation between $T$ and $V$ the same as for the thermal limit, i.e. $eV \simeq 3.63 k_B T$ [19]. We further note that, when the phonons can be considered as being in thermal equilibrium with electrons in the current carrying state of a *ballistic* point contact, their effective temperature is related to the voltage by similar equation [20]. Thus, we take $V\,[\text{mV}] \simeq 0.31 T\,[\text{K}]$ for the correspondence between temperature and voltage scales. This choice of $V(T)$ relation is also confirmed by magnetic field measurements since it leads to the same relative decrease in Kondo peak, comparing Figs. 6 and 9.

The fit of the normalized Eq. (6) to the data for three of our contacts is shown in Fig. 10. It yields Kondo temperatures in a reasonable accord with the bulk value $T_K = 34$ K cited in Ref. 18. Note that the

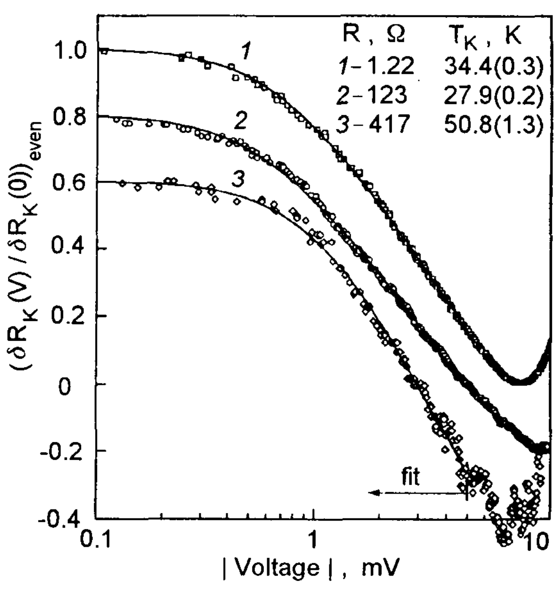


*Fig. 10.* The fit of the empirical relation Eq. (6) to the experimental data for the CuFe (0.1 at.%) contacts with $R_0 = 1.22\ \Omega$ ($d = 33.8$ nm); 123 Ω ($d = 3.0$ nm), and 417 Ω ($d = 1.6$ nm). The voltage scale is translated in a temperature scale using $V\,[\text{mV}] = 0.31T\,[\text{K}]$, see text. The corresponding Kondo temperatures inferred from the fit are 34.4 (0.3); 27.9 (0.2); and 50.8 (1.3) K with standard deviations shown in brackets. The curves for $R = 123\ \Omega$ and 417 Ω are displaced along $Y$ axis for clarity.

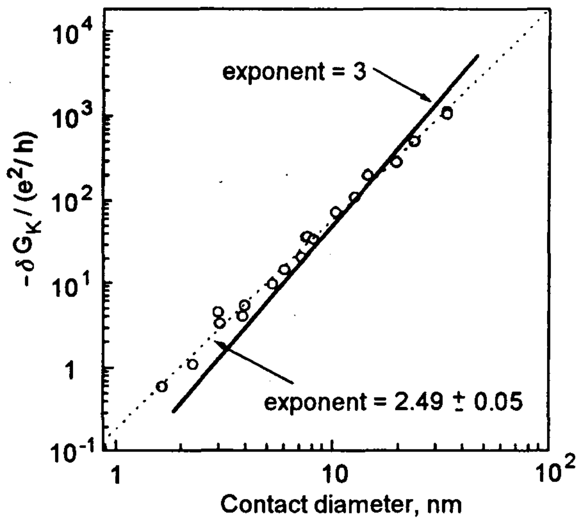


*Fig. 11.* The amplitude of the zero bias minimum in the conductance in units of $e^2/h$ plotted as a function of the contact diameter $d$. The solid line is the unitary limit for the average number of impurities in the contact volume (proportional to $d$). The broken line is a least-squares fit to the experimental data.

value of the parameter $\theta$ is only weakly dependent on the ordinate scale, and is not changed much even if we use the original $R$ scale for the point contact resistance, without any scaling and offsets. Comparing between Fig. 10 and Fig. 6 one sees that for the smallest contacts not only the increase but also the fluctuations of Kondo temperature are the largest. This is due to the fact that the number of impurities in the effective contact region becomes small.

In the unitarity limit, $k_BT$, $eV \ll k_BT_K$, each impurity is expected to reduce the conductance by an amount of order $e^2/h$. Figure 11 plots $-\delta G_K = \delta R_K/R_0^2$ divided by $e^2/h$ as a function of $d$ for the CuFe 0.1 at.% alloy. The solid line gives the unitarity limit for the average number of impurities in the volume $\pi d^3/6$ of the contact. The observed dependence $\delta R_K/R_0 \propto d^{0.5}$ results in $\delta G_K(d)$ close to $\simeq d^{2.5}$ with absolute values just as expected. The deviation from the $d^3$ dependence can thus be attributed to the gradual transition from ballistic to diffusive transport for increasing contact sizes.

Unfortunately, a reliable determination of small changes in Kondo temperature with contact size from voltage dependences is hindered by scattering in the data. We may try to solve this problem indirectly, through the quite clear change in magnetic field suppression of the Kondo peak with contact size. In order to do this we adopt the reasonable view [18,21], supported by experimental results for temperatures below $T_K$ [6] and theoretical predictions for perturbative regime [21], that nonzero magnetic fields can be incorporated in the effective temperature through the relation

$$T_{\text{eff}} = \sqrt{T^2 + \beta^2 H^2}\,. \qquad (7)$$

Here the units for $T$ and $H$ are matched through the relation $\mu_B H = k_B T$ which is equivalent to 0.67 K per Tesla. The coefficient $\beta$ remains somewhat uncertain. For the perturbative case it equals 0.32 for $H/T \ll 1$ and 0.77 for $H/T \gg 1$ [21]. According to Ref. 6 for $T < T_K$ and $H < H_K$, coefficient $\beta \sim 1$ and we shall now use this value for further estimates. Thus, we can write

$$f(H, T) \equiv \frac{\delta R_K(T, H)}{\delta R_K(0, 0)} = 1 - b \ln \left[ 1 + \frac{T^2 + H^2}{\theta^2} \right] \qquad (8)$$

and

$$\Delta\theta = (\partial f/\partial\theta)^{-1} \Delta f\,, \qquad (9)$$

where

$$\partial f/\partial\theta = (2b/\theta) \left[ 1 + \frac{\theta^2}{T^2 + H^2} \right]^{-1}. \qquad (10)$$

From Fig. 9 we obtain $\Delta f \simeq 0.2$ at $T = 0.5$ K and $H = 12$ T. Now the coefficient $b$ enters explicitly into our estimate. From the fit of Fig. 10 we get $b = 0.21$, but its value should be about two times smaller due to the following reasons. Our determination of the Kondo temperature ($T_K = 34$ K) leads to $V_K = 10.7$ mV, which is located correctly at energies (or, equivalently, temperatures) just about an order of magnitude larger than the characteristic energy corresponding to the bending of the experimental data towards the saturation of the unitarity limit. In the point contact case (Fig. 10), at this voltage bias the Kondo contribution is already completely buried under the spreading resistance and phonon induced background (and thus we conventionally take it equal to zero). In contrast, the empirical bulk $\rho_m(T)$ dependence at the Kondo temperature has dropped to only one half of its full value (see Fig. 4 of Ref. 18). Thus, for the correct Kondo contribution the scale in Fig. 10 should be approximately reduced by one half leading to $b \simeq 0.11$ corresponding to the bulk value. The same considerations lead to the conclusion that the value of $\Delta f$ obtained from experimental plots in Fig. 9 should also be halved ($\Delta f \simeq 0.1$), and since both corrections cancel, we obtain $\Delta\theta = 1.3$ K and $\Delta T_K \simeq 20$ K, independently on the ordinate-scale values. Thus, the Kondo temperature approximately doubles upon increasing the resistance from 1 Ω to about 30 Ω. Certainly, our estimate is rather crude due to many approximations and the fact that the change of the Kondo temperature obtained is not small compared with the Kondo temperature itself. However, we believe it correctly reflects the expectations [10] that in case of Fe impurities an increase in the Kondo temperature should be found, but much less pronounced than for Mn impurities [4,8].

If we replot the $x$ axis of Fig. 9 using the voltage and temperature relations mentioned above, Fig. 9 (top scales) can be directly compared with Fig. 6. The curves are indeed consistent in shape and absolute value. However, the size effect is about 5 times more pronounced in the field dependence. We do not have an explanation of this difference at the moment.

To make a quantitative comparison of $\Delta T_K$ with the predictions of the Zarand-Udvardi theory [10], we can try to use simplified estimates based on the standard formula for the Kondo temperature (Eq. (1)), where $J$ is the exchange interaction energy of conduction electrons with the magnetic impurity which is supposed to remain unchanged. Since $(\partial/\partial\rho)(1/J\rho) = -1/J\rho^2$, we obtain a simplified expression for the Kondo temperature $T_K$ modified due to the change of LDOS by $\delta\rho$:

$$T_K = T_K^{\mathrm{bulk}} \exp(\delta\rho/\gamma\rho_0)\,, \qquad (11)$$

where $\gamma = J\rho_0$ and $\delta\rho/\rho_0$ is the relative change of the electron LDOS at the Fermi level due to the quantum interference effect. From the Eq. (1) it follows that for Mn and Fe impurities in Cu $\gamma$'s are equal to 0.06 and 0.12, respectively. For point contacts of about $R_0 = 130\ \Omega$ ($d \simeq 2.6$ nm) $\delta\rho/\rho_0$ can be estimated from the observed huge increase in Kondo temperature for CuMn alloy, since here the Fermi-liquid parabolic dependence is available (see Fig. 11 in Ref. 8). Depending on which relations one takes between $V$ and $T$, on the one hand, and $T^*$ and $T_K$ in the $\rho_m(T) = \rho_m(0)[1-(T/T^*)^2]$ formula, on the other hand, we estimate a value for $T_K$ in the range 40–400 K which leads to $\delta\rho/\rho_0 \simeq 0.4$–$0.7$. When this quantity is substituted into Eq. (11), a Kondo temperature of up to 900–6000 K is found for the CuFe point contacts with a resistance $R \simeq 100\ \Omega$, although the exponent increases the Kondo temperature only by a factor of $\sim 100$ instead of $\sim 10^4$. It is not surprising the oversimplified formula (11) is not sufficient for a correct quantitative description of the dramatic difference in size dependence observed for CuMn and CuFe alloys with the bulk Kondo temperatures differing more than three orders of magnitude. The theory [10] predicts that the increase in the Kondo temperature depends mainly on the behavior of LDOS $\rho(\varepsilon)/\rho_0$ in the energy range of order $T_K^{\mathrm{bulk}}$ near $\varepsilon_F$. Since $T_K^{\mathrm{bulk}}(\mathrm{CuFe}) \gg T_K^{\mathrm{bulk}}(\mathrm{CuMn})$, using the same $\rho$-enhancement in formula (11) for Mn and Fe impurities, we may greatly overestimate effect of the Kondo temperature enhancement for CuFe alloy in case of a sharp resonance increase in $\rho(\varepsilon)$ at $\varepsilon_F$ due to the quantum interference of conduction electrons.

## Conclusions

The Kondo effect in nanosized 3$D$ point contacts of CuFe dilute alloys appears to be size dependent qualitatively in the same way as it was found for CuMn material. As the contact size decreases the Kondo temperature increases. However, quantitatively a dramatic difference exists between these Kondo alloys. While for CuMn an increase in Kondo temperature can be observed up to many orders of magnitude, from the bulk value of 0.01 K up to tens and hundreds K in contacts of several nanometers in diameter, for the CuFe contacts of the same size an increase does not exceed several tens K, i.e., the bulk Kondo temperature 30 K increases by only a factor of $\simeq 2$. Qualitatively, such a difference can be explained by the LDOS fluctuation theory of Zarand and Udvardy [10], but to account for it quantitatively, the detailed numerical calculations and further development of the theory are needed.

Following Zarand and Udvardi [10], we suggest that the effect of LDOS fluctuations was not seen in the previous study of size-effect in Kondo scattering for thin film and nanofabricated wires since only alloys with relatively high Kondo temperature were investigated (CuFe, CuCr, and AuFe) [5,6,8] up to now. We speculate that in the recent study of thin films and wires of CuMn 0.1 at.% [22] an anomalous temperature dependence of resistivity was observed which could well be due to the effective Kondo temperature increase induced by the LDOS fluctuations in those mesoscopic samples.

The local density of states fluctuations in ultrasmall point contacts may lead to a number of other interesting effects, such as size dependence of the RKKY interaction in spin glasses [8], a modification of the heavy fermion state with decreasing contact size, and gradual metal-insulator transition for contacts with decreasing size and increasing disorder in atomic positions. Also the superconducting properties of ultrasmall weak links can be affected.

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