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ABSTRACT

We report a preliminary test of whether muon diffusion in copper is limited by conduction electron scattering or by nonadiabatic quantum damping as proposed by Kondo. Drift of the muon with electron wind when a current is passed through the sample is not observed, indicating that electron scattering is relatively weak and supporting the Kondo quantum damping mechanism.

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SEARCH FOR MUON DRIFT IN COPPER

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In this note we report the result of a preliminary search for muon drift in copper. The experiment was designed to distinguish between two theories[1,2] of the muon hopping rate ν, which has been measured in copper over a wide range of temperature[3-6] and is shown in Fig. 1. The solid curve in the figure is the theory of Kondo[1] fitted to copper and covering three distinct temperature ranges. At temperatures above 50K the muon tunnels from site to neighboring site at fixed range $\underline{a}$ with the absorption of a phonon that supplies the energy associated with small polaron formation. (Only at still higher temperature would the muon be expected to hop over the potential barrier between adjacent sites.) At temperatures from 0.5K up to 50K the small polaron tunnels coherently without phonon absorption. At temperatures below 0.5K the hopping rate becomes independent of temperature as a result of residual broadening of the polaron energy.[7]

The diffusivity for fixed-range hopping

$$\mathrm{Diff} = \nu a^2 = V^2\tau \tag{1}$$

may be written as the product of the square of a transfer velocity and a relaxation time. Kondo shows that the transfer velocity for coherent hopping is given by

$$V = \Delta_{eff}a = \Delta(\pi T/D)^K a \tag{2}$$

Here Δ_{eff} is the transfer integral of the muon dressed by the screening cloud of electrons, Δ is the bare transfer integral, D is the width of the conduction band, and K is the muon-electron coupling constant. The factor $(\pi T/D)^K$ renormalizes the muon mass and arises from Anderson orthogonalization.[8]

One expects for the relaxation of a muon in a narrow band

$$1/\tau = \Gamma = \pi g\ k_B T/\hbar \qquad (3)$$

which is Korringa scattering[9] of the screened muon with coupling constant $\underline{g} = 2V_o^2\rho^2$, where V_o is the scattering potential and ρ the density of electron states. Kondo finds that Γ should be multiplied by a vertex correction $(D/T)^g$ that may be quite large. But for $V\tau$ less than the near neighbor separation $\underline{a}$ the muon does not move coherently through the band with occasional scattering but instead hops from site to site. Kondo concludes that a sufficiently localized hopping muon is damped not by Korringa scattering but by the inability of the screening electrons to adiabatically follow the muon. The damping of the muon arises dynamically with

$$1/\tau = \Upsilon = (\pi K/\cos\pi K) k_B T/\hbar \qquad (4)$$

Yamada[2] has developed a very similar theory of the transfer velocity but has assumed that the hopping muon is damped by ordinary Korringa scattering as given by Eq. (3) rather than by Eq. (4). As the diffusion data of Fig. 1 do not readily distinguish the two theories we have been led to devise an experiment that may differentiate between dynamic damping of a hopping muon and Korringa scattering.

If the muon is damped through scattering there should be a substantial drag force on the muon from electron wind[10] when an electron current is passed through the sample. On the other hand, if the muon is damped by nonadiabatic conduction electron screening, then any force exerted by electron wind may be too small to induce hopping. As we report below, any possible drag-induced hopping is within our error and is less than 5% of the spontaneous hopping. We conclude that muon damping is not produced by electron scattering but must be associated with a stronger process.

We now examine the dynamics of interacting muons and electrons in the presence of an electric field in two limits, band motion and fixed-range hopping. We first write for the mean velocity of a band muon:

$$M\, dV/dt + MV/\tau = eE + \Gamma\, Mv \qquad (5)$$

where M is the band mass of the muon and V and v are the muon and electron drift velocities, respectively. For electron scattering the damping rate $1/\tau$ is given by Γ. Note that the muon is driven by two forces, the force of the electric field and the force of the electron wind.[10] As long as the electron drift velocity is less than the muon band velocity $\Delta_{eff}a$ we may expect the muon to drift at the velocity of the electron wind. The rate at which the muon moves from cell to cell will be proportional to the root-mean-square velocity and given by:

$$\nu = \Delta_{eff} + \tfrac{1}{2}\, v^2/a^2\Delta_{eff} \qquad (6)$$

In the limit of short relaxation times and fixed range hopping we compute the time for a muon to leave a sphere of radius <u>a</u> assuming a drift velocity $\bar{V}$ superimposed on the diffusive motion. We obtain in this way for the hopping frequency:

$$\nu = 2\, V^2/[(\bar{V}^4\tau^2 + 4\, a^2\bar{V}^2)^{1/2} - \bar{V}^2\tau] \qquad (7)$$

For the drift velocity $\bar{V} < \nu_o a$ we obtain on expansion:

$$\nu = \nu_o + \bar{V}^2/\nu_o a^2 \qquad (8)$$

In the opposite limit of $\bar{V} > \nu_o a$ we obtain $\nu = \bar{V}/a$.

The diffusion of muons in copper has been studied extensively by analyzing the muon spin relaxation[6]. The spin relaxation function in a transverse magnetic field is described by a function developed by Kubo and Tomita[11]

$$G(t) = e^{-(\sigma/\nu)^2(e^{-\nu t} - 1 + \nu t)} \quad (9)$$

where σ^2 is the second moment of the dipolar broadening produced by the copper nuclei and ν as before is the hopping frequency. For times t short compared with $1/\nu$ we obtain $G(t) = e^{-\frac{1}{2}\sigma^2 t^2}$ which is the usual gaussian line shape with rms width σ. On the other hand, for times long compared with $1/\nu$ we obtain exponential decay $G(t) = e^{-\sigma^2 t/\nu}$. Now, if the hopping rate is low compared with σ we have gaussian relaxation with exponential decay only at very long times. But if the hopping rate is rapid compared with σ, the relaxation is gaussian only at very short times with most of the decay exponential. In this limit the resonance line is lorentz in shape with a half-width σ^2/ν. This is the motionally narrowed limit

$$G(t) = e^{-(\sigma^2/\nu)t} \quad (10)$$

The technique used at TRIUMF was to stop a highly polarized muon beam available parasitically at M-20, the "surface-tune", in a thin copper foil located in an analyzing apparatus, the LBL/UCB Eagle detector. This detector has a transverse field of 67 gauss in the vertical direction with four telescopes, left, right, forward, backward, in the precession plane. The elapsed-time histograms of decay electrons are analyzed with the function

$$Y(t) = Y(0)e^{-t/\tau}[1 + A\, e^{-(\sigma^2/\nu)t} \cos(\omega t + \phi) + BG \qquad (11)$$

where $\tau = 2.20\mu$ sec is the natural lifetime of the muon, A is the overall average analyzing power, ϕ is the phase of each detector pattern, and BG is the constant background, which is of order 5% of the signal. The frequency $\omega = \gamma H$ is extracted from the fit. Even though it was not possible to optimize the beam tuning, about 50% of the muons stopped in the thin copper foil, which was sandwiched between foils of mu-metal. The muons showed no precession asymmetry in this backing material.

As shown in Fig. 1, low temperature hopping rates in copper are of the order of 10^5 in the temperature range between 4.2 and 100K. Below 4.2K the hopping rate increases with decreasing temperature to about 10^6. (Above 100K the hopping rate increases to 10^7 or higher.) By driving an electron current through the sample we might expect to produce muon drift, increasing the effective hopping frequency ν and enhancing the motional narrowing. At a hopping rate $\nu_o = 10^5$ the corresponding drift velocity $\bar{V} = \nu_o a$ is 4×10^{-3} cm/sec. (This velocity is to be compared with the muon band velocity of about 13 cm/sec.) For the electron wind to move at $\nu_o a$ the required current density J = Nev is 50 A/cm^2. An oxygen-free polycrystalline copper foil of 0.9999 purity[12] and 0.005 cm thickness was cut and arranged so that current flowed along and against the magnetic field in six parallel alternating segments. At the maximum current supplied to the foil of 1.5 A the current density was 700 A/cm^2, enough to produce an effective muon hopping rate in excess of 10^6 if the muons drift with the electron wind.

The temperature of the copper foil was set and regulated with a JANUS He-Flow cryostat and the precessional relaxation rate was extracted for several temperatures and currents supplied to the foil. The errors were obtained from the fitting program MINOS[13] and are relative errors that do not include possible systematic errors. Our data, averaged over left and right telescopes, are shown in Fig. 2. To within experimental error we observe no significant decrease in σ^2/ν with an uncertainty of 5% at the lowest temperatures, where we might have expected to observe narrowing.

We write from Eq. (8) for the muon hopping rate in the presence of spontaneous hopping and drift

$$(\nu - \nu_o)/\nu_o \cong (\bar{V}/\nu_o a)^2 < .05 \qquad (12)$$

which gives for the upper limit on the muon drift velocity

$$\bar{V} = (\Gamma/\gamma)v < 0.2\ \nu_o a \qquad (13)$$

at T = 6K with an electron wind of v = .06 cm/sec. From the observed hopping rate and Kondo's theory we obtain $\gamma = 4.3 \times 10^{12}$ sec^{-1} at 6K. The inequality of Eq. (13) then leads to $\Gamma < .014\ \gamma$ or $g < .05$. It is clear from the obtained inequality either that muon diffusion is substantially more strongly damped than would be expected from Korringa scattering or that the expected muon drift is inhibited.

Finally we compare our obtained upper limit for the Korringa damping constant $g < .05$ with estimates of muon-electron scattering. Jackle and Kehr[13] have analyzed electron-muon scattering in metals and provide the estimate for the damping rate at $T > \Delta$

$$\Gamma = n\ \sigma v_F\ T/T_F \qquad (14)$$

with n the electron concentration, v_F the Fermi velocity, T_F the Fermi temperature, and σ the cross-section for screened Coulomb scattering[14], which is approximately $4\pi/k_s{}^2 = \pi^2 a_o/k_F$ where $1/k_s$ is the Thomas-Fermi screening length and a_o is the Bohr radius. Substituting appropriate values for copper into Eq. (14) we obtain an expression of the form of Eq. (3) with coupling constant $g = 2k_F a_0/3\pi$ which is about 0.15 and somewhat greater than our obtained limit for electron scattering.

We conclude that the absence of muon drift in the presence of electron wind argues for something other than a diffusing muon damped by electron scattering as assumed by Yamada. Were the muon damped in this way the hopping rate should have been of the order of v/a even for wind velocities substantially less than muon band velocities. The fact that drift was not observed argues either that muon damping is substantially stronger as proposed by Kondo, or that drift may possibly be inhibited by the structure of the muon state in a metal.

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REFERENCES

1. J. Kondo, Physica 125B, 279 and 126B, 377 (1984). An informal report (in Japanese) has been published in Kotai Butsuri 20, 11 (1985). See also Physica 132B, 303 (1985) for an analysis of heavy particles in metals.
2. Kosaku Yamada, Prog. Theor. Phys. 72, 195 (1984).
3. V. G. Grebinnik, I. I. Gurevich, V. A. Zhukov, A. P. Manych, E. A. Meleshko, I. A. Muratova, B. A. Nikol'skii, V. I. Selivanov, and V. A. Suetin, Soviet Phys. JETP 41, 777 (1976).
4. C. W. Clawson, K. M. Crowe, S. S. Rosenblum, S. E. Kohn, C. Y. Huang, J. L. Smith, and J. H. Brewer, Physica 109 & 110B, 2164 (1982) and Phys. Rev. Letters 51, 114 (1983).
5. R. Kadono, J. Imazato, K. Nishiyama, K. Nagamine, T. Yamazaki, D. Richter, and J. -M. Welter, Hyp. Int. 109, 17 (1984) and Phys. Lett. 107A, 279 (1985) and 109A, 61 (1985).
6. Y. Fukai and H. Sugimoto, Adv. in Phys. 34, 263 (1985). See also A. Schenck, Muon Spin Rotation Spectroscopy: Principles and Applications in Solid State Physics, Adam Hilger Ltd., Bristol and Boston, 1985.
7. Similar results have been deduced from trapping rates in aluminum, K. W. Kehr, Hyp. Int. 17-19, 63 (1984). Y. Fukai has interpreted the quench-recovery of hydrogen in tantalum to yield similar behavior for diffusing protons, Japan J. Appl. Phys. 23L, 596 (1984).
8. P. W. Anderson, Phys. Rev. Lett. 18, 1049 (1967). See also J. Kondo, Physica 84B, 40 (1976) and Kosaku Yamada, Akio Sakurai, and Motomu Takeshige, Prog Theor. Phys. 70, 73 (1983).
9. J. Korringa, Physica 16, 601 (1950).

10. A. K. Das and R. Peierls, J. Phys. C6, 2811 (1973) and C8, 3348 (1975). See particularly the equivalence theorem in the first reference. A.K. Das, Helv. Physica Acata 49, 829 (1976).

11. R. Kubo and K. Tomita, J. Phys. Soc. Japan 9, 45 (1954).

12. From measurement of the resistivity of the copper foil and connecting leads, the residual resistivity ratio of the foil must have been in excess of 100 with the conduction electron relaxation time τ longer than 2.5×10^{-12} sec.

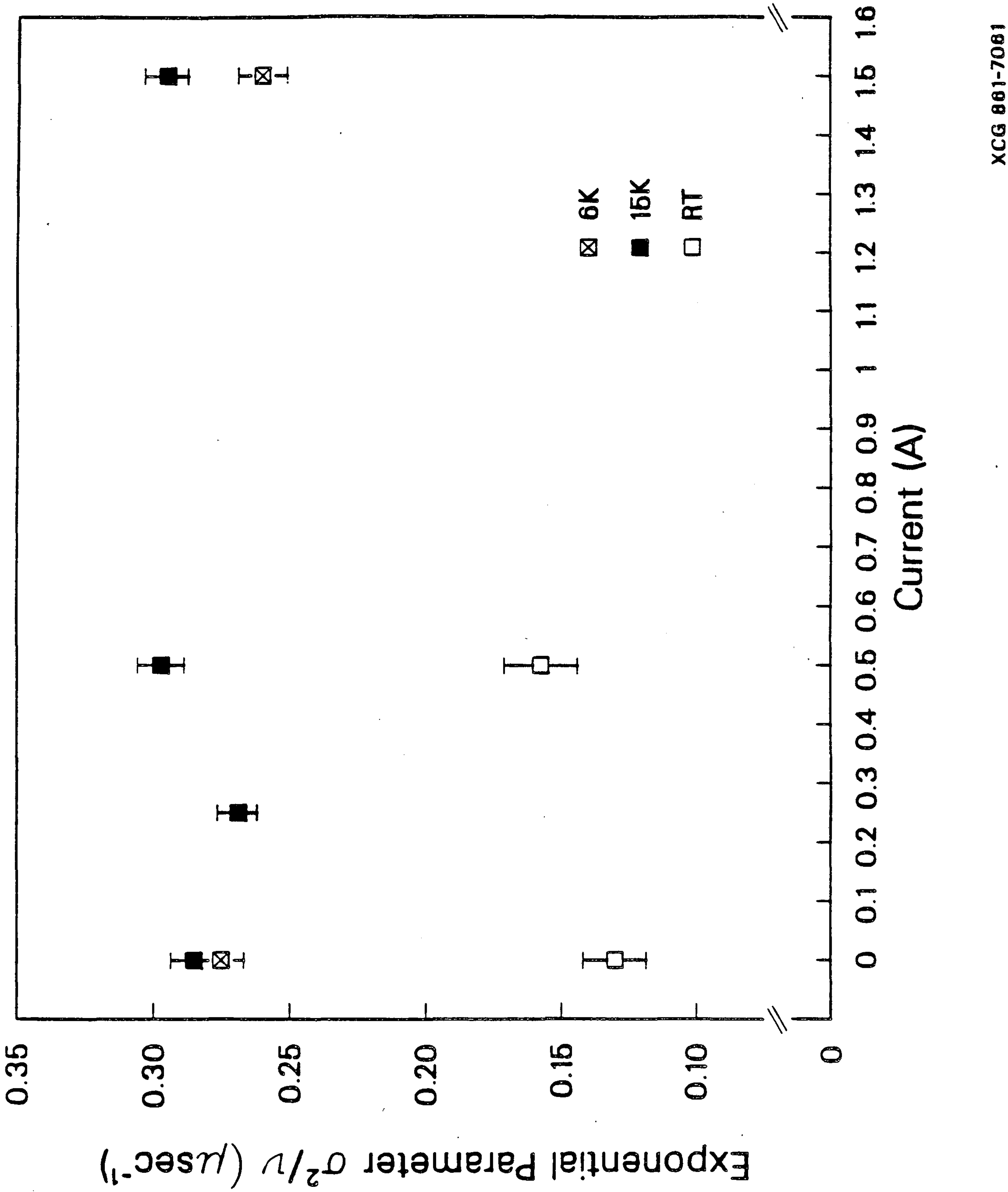
13. F. James and M. Roos, editors, CERN Computer Centre Report D506/D516, ammended 20 June 1974, page F401(1).

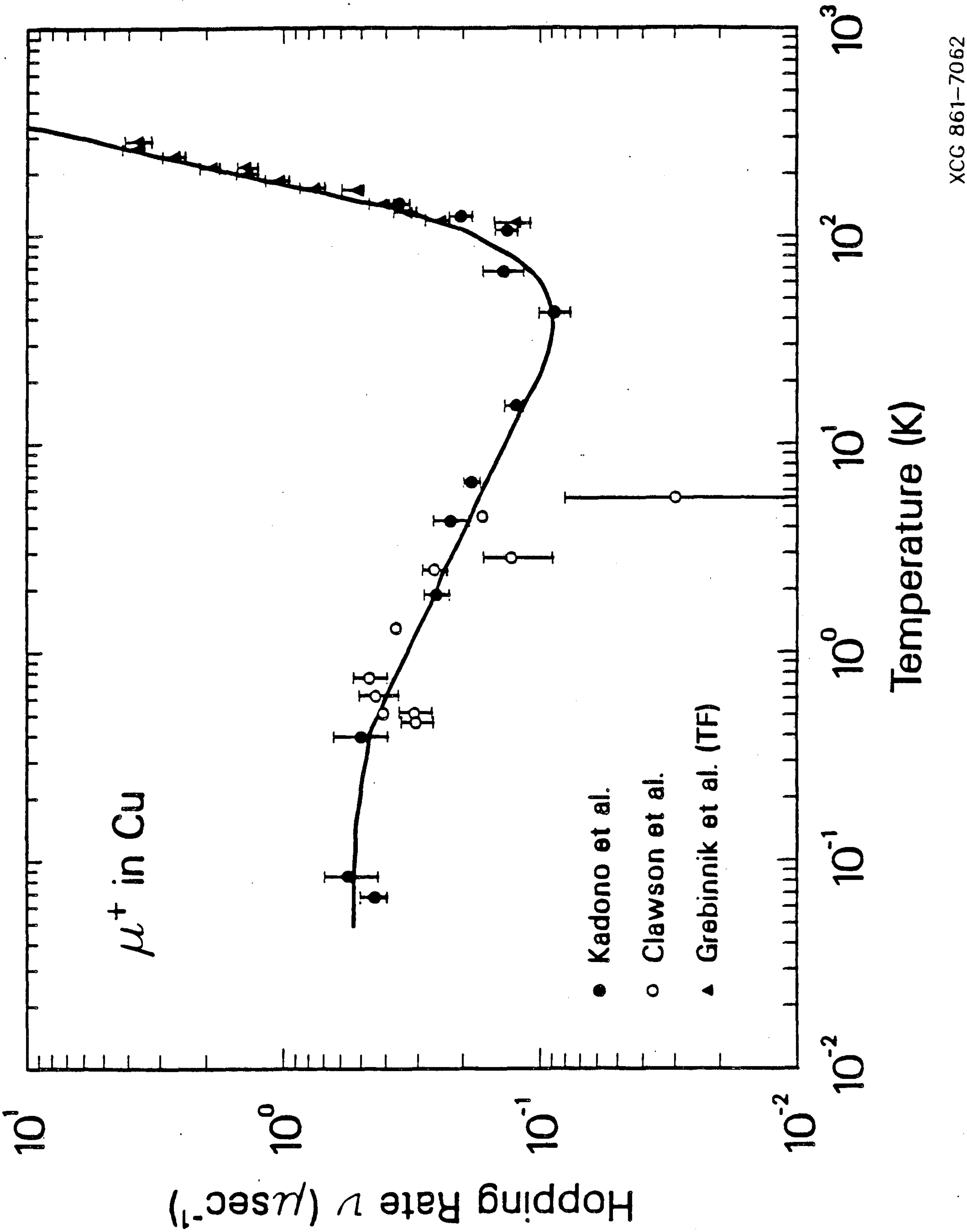
14. J. Jackle and K. W. Kehr, J. Phys. F13, 753 (1983).

5. J. D. Jackson, Classical Electrodynamics, Wiley, Second Edition, 1975. Section 13.7.

FIGURE LEGENDS

1. Observed values of the hopping rate ν as a function of temperature. The measurements of Kadono et al.[5] and of Clawson et al.[4] were carried out on the zero field (ZF) spin relaxation function. The measurements of Grebinnik et al.[3] were carried out in transverse field (TF). The solid curve is the theory of Kondo fitted to copper.
2. Data for T=6K, 15K and room temperature (RT) averaged over left and right telescopes. No significant decrease in the exponential parameter σ^2/ν is observed as a function of current.


Exponential Parameter σ^2/ν (μsec^{-1})
0.35
0.30
0.25
0.20
0.15
0.10
0
Current (A)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
6K
15K
RT
XCG 861-7061


μ^+ in Cu
Kadono et al.
Clawson et al.
Grebinnik et al. (TF)
Temperature (K)
Hopping Rate ν (μsec^{-1})
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
XCC 861-7062