KFKI
24/1968

SOME NEW EFFECTS IN ZERO BIAS ANOMALIES CAUSED BY PARAMAGNETIC IMPURITIES

A. Zawadowski and J. Sólyom

Lecture presented at 11th International Conference on Low Temperature Physics
St.Andrews, Scotland, 21-28 August 1968.

HUNGARIAN ACADEMY OF SCIENCES
CENTRAL RESEARCH INSTITUTE FOR PHYSICS

BUDAPEST

Printed in the Central Research Institute for Physics, Budapest
Kiadja a Könyvtár- és Kiadói Osztály. O.v.: dr. Farkas Istvánné
Szakmai lektor: Menyhárd Nóra Nyelvi lektor: Hargitai Csaba
Példányszám: 210 Munkaszám: 3951 Budapest, 1968. szeptember 19.
Készült a KFKI házi sokszorositójában. F.v.: Gyenes Imre

SOME NEW EFFECTS IN ZERO BIAS ANOMALIES CAUSED BY PARAMAGNETIC IMPURITIES

A. Zawadowski and J. Sólyom

Institut Max von Laue - Paul Langevin, 8046 Garching, Germany, and Central Research Institute for Physics, Budapest, Hungary+

Recently tunneling diodes /M-MO-M/ containing paramagnetic impurities are investigated experimentally [1] . A possible explanation of some zero bias anomalies observed on these diodes is worked out by the authors [2] . This explanation considers the Kondo scattering of electrons on paramagnetic impurities. This scattering can depress the electron spectrum around the impurities in the case of inhomogeneous impurity distribution. As the Kondo effect occurs in the energy region of Fermi level, this depression may be observed by tunneling experiments. Two consequences of this theory are presented here.

1/ Coherence length

Let us consider, as an example, a barrier with infinite heights $(x<0)$ and an electron gas on its right side $(x>0)$. The effect of paramagnetic impurities on the local energy spectrum of electrons at the barrier is determined. In tunneling those electrons play an important role whose wave vectors have small components in the plane of the barrier, $k_\parallel \approx 0$. We consider only wave vectors $k_\perp$ perpendicular to the barrier. The surface of the barrier is taken to be unit. The Dyson equation for the one electron Green function has to be solved:

$$\mathcal{G}_\omega(x,x') = \mathcal{G}^{(0)}_\omega(x,x') + \int dx'' \, \mathcal{G}^{(0)}_\omega(x,x'')\, c(x'')\, t(\omega)\, \mathcal{G}_\omega(x'',x') \qquad (1)$$

where $c(x'')$ is the distribution function of impurities and $t(\omega)$ denotes the scattering amplitude* due to impurities. The free electron Green function can be calculated easily, e.g. at $\omega = 0 \pm i\varepsilon$

$$\mathcal{G}^{(0)}_{0\pm i\varepsilon}(x,x') = \frac{2}{\pi v_F}\sin(k_F x)\sin(k_F x')(\mp\pi i) + \frac{2}{\pi v_F}\left\{F(x-x') - F(x+x')\right\} \qquad (2)$$

where k_F is the Fermi wave number, $v_F = \frac{k_F}{m}$ the Fermi velocity,

$$F(u) = \sin(k_F u)\left\{-\frac{\pi}{2} + si(\Delta k_c u)\right\} \qquad (3)$$

and Δk_c is a cutoff in the exchange Hamiltonian, which restricts the interaction to the neighbourhood of the Fermi energy, namely $(E_F - v_F\Delta k_c) < E < (E_F + v_F\Delta k_c)$. It is supposed that $\Delta k_c \ll k_F$. The function $F(x,x')$ can be neglected if

$$|x|,\ |x'| \ll \pi\frac{1}{\Delta k_c} = \xi_c \qquad (4)$$

where ξ_c is the coherence length, determined by the cutoff. In the opposite limit $F(x-x') - F(x+x') \sim -\pi$ which would lead to a cancellation in our final result. It will be supposed that all impurities are found much nearer to the barrier than ξ_c. The energy spectrum $\rho(k_\parallel \approx 0;\omega)$ averaged over a small distance $(<\xi_c)$ at the barrier can be derived by solving (1) making use of (2) and the spectral representation, we get

$$\rho(k_\parallel \approx 0;\omega) = \rho_0(k_\parallel = 0)\,\mathrm{Im}\left\{\frac{1}{1 + i\pi\rho_0(k_\parallel = 0)\,t(\omega + i\varepsilon)\int c(x)\,dx}\right\} \qquad (5)$$

where $\rho_0(k_\parallel \approx 0) = \frac{1}{\pi v_F}$ is the unrenormalized local density of electron states. The measure of the depression in the energy spectrum caused by the impurities is the following quantity

$$Z(\omega) = \frac{\rho(k_\parallel \approx 0;\omega)}{\rho_0(k_\parallel \approx 0)} = \frac{1}{1 + 2\rho_0 N_i\,|\mathrm{Im}\,t(\omega)|} < 1 \qquad (6)$$

where only the imaginary part of t is taken into account, $\rho_0 = \frac{k_F m}{2\pi^2}$ is the density of states $N_i = \left(\frac{\pi}{k_F}\right)^2 \int c(x)\,dx$ is the thickness of the impurity layer in atomic distance.

If the scattering amplitude $\mathrm{Im}\,t(\omega)$ exhibits a maximum in the neighbourhood of the Fermi energy, this causes a relative decrease of the density of states in this energy region. This change described by (6) can be observed investigating tunneling diodes containing paramagnetic impurities at the barrier.

The distance of the impurities measured from barrier has to be smaller than ξ_c . The change in the density spreads over a distance, comparable with ξ_c . This effect is similar to the Friedel oscillation which due to the lack of any cutoff Δk_c occur only over atomic distances. The existence of a cutoff follows from the derivation [3] of the Kondo Hamiltonian on the basis of the Anderson model. The energy $v_F \Delta k_c$ is related to the energy of localized "d" level, measured from the Fermi level. The coherence length may be estimated in atomic distances as $\frac{E_F}{v_F \Delta k_c} \sim \frac{k_F}{\Delta k_c}$

2/ Dependence on the impurity concentration /selfconsistency/.

The amplitude of the observable zero bias anomaly can be estimated on the basis of (6) , considering the relative increase of the dynamical resistivity R/V/ at zero temperature. We obtain

$$Max \left\{ \frac{R(V)}{R_0} \right\} = \left(Min\{z\} \right)^{-1} = 1 + 2\rho_0 N_i \, Max \{ |Im\, t(\omega)| \} \sim 1 + \frac{2}{\pi} N_i \quad (7)$$

where the scattering amplitude is replaced by $[\pi \rho_0]^{-1}$ which is derived by Hamann [4] , and exhibits the maximum at zero energy /zero bias/.

In the case of many impurities the scattering amplitude is modified because the electron spectrum is depressed at the impurity site in the energy region under consideration.

There are two effects if the average electron spectrum entering into the Kondo problem is changed by a factor $\frac{\langle \rho \rangle}{\rho_0} = \langle z \rangle < 1$

a/ the energy width of the anomaly becomes narrower by increasing the impurity concentration because of the effective Kondo temperature is essentially decreased, namely

$$k T_K (\rho = \rho_0 \langle z \rangle) = E_c \exp \left\{ \frac{N}{2\rho_0 J \langle z \rangle} \right\} \ll k T_K (\rho = \rho_0) \quad \text{for } \langle z \rangle < \frac{1}{2}$$

b/ strong /nonlinear/ dependence of the amplitude on the impurity concentration, namely $|Im\, t(0)| \sim \frac{1}{\pi \rho_0 \langle z \rangle}$ and replacing this value into (7) we get

$$Max \left\{ \frac{R(V)}{R_0} \right\} \sim 1 + \frac{2}{\pi} N_i \frac{1}{\langle z \rangle}$$

61.792

Extending experimental investigations of zero bias anomalies in diodes containing magnetic impurities would give information about the cutoff Δk_c and the energy dependence of the scattering amplitudes in a large energy region. These informations are not available from other experiments at the present time. The change in the electron spectrum might cause observable effect in NMR experiments if $\frac{\Delta k_c}{k_F} \ll 1$

We are grateful to Dr. E. Müller-Hartmann for a discussion of the coherence length.

References

+ Address of J.S. and permanent address of A.Z.

* It is called self-energy in Ref. [2] .

[1] A.F.G. Wyatt and D.J. Lythall, Physics Letters 25A, 541 /1967/, Phys. Rev.Lett. 20, 1361 /1968/
F. Mezei, Phys. Lett. 25A, 534 /1967/
L.Y.L. Shen, Bull. of Amer. Phys. Soc. 13, 476 /1968/

[2] A. Zawadowski, Proceedings of 10th International Conference on Low Temperature Physics, Moscow, Vol. IV p.336.
J. Sólyom and A. Zawadowski, Physics of Condensed Matter 7, 325 /1968/ and 7, 342 /1968/.

[3] J.R.Schrieffer and P.A. Wolf, Phys. Rev. 149, 491 /1966/

[4] D.R. Hamann, Phys. Rev. 158, 570 /1967/