PAIRBREAKING IN S-WAVE SUPERCONDUCTORS BY TWO-CHANNEL KONDO IMPURITIES

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Abstract We propose dynamical defects with a rotational degree of freedom in a metal as a possible realization of two-channel Kondo systems. When the $\ell = 0$ state of the defect is blocked, the impurity exhibits a Kramers doublet ground state. We consider the pair breaking effect of a finite density of this type of two-channel Kondo impurities in an s-wave superconductor, using an auxiliary particle representation for the impurity, and the BCS model for the superconductor.

Several experiments on mesoscopic systems indicate an apparently non-vanishing electron dephasing rate $1/\tau_\phi$ at low temperatures T [1]. The origin of this dephasing saturation is of fundamental interest in condensed matter physics as well as relevant for the design of nanoscale devices involving quantum phase coherence. The strong dependence of the saturation value of τ_ϕ on the type of material and on the sample preparation technique hints at a dephasing mechanism which is not intrinsic to the electron liquid. It has been proposed that dynamical structural defects in the crystal structure like two-level systems (TLS), coupled to the electron system, could cause dephasing at low T. In order to account for the experiments this requires either a distribution of level splittings δ, $P(\delta) \propto 1/\delta$ [2], or a sizable fraction of TLS with vanishing δ which produce a two-channel Kondo (2CK) effect [3]. The 2CK effect implies a non-vanishing $T = 0$ dephasing rate because of its finite zero-point entropy $S(0) = k_B \ln\sqrt{2}$ [4]. At present, there exists no microscopic model to explain a level splitting distribution $P(\delta) \propto 1/\delta$. On the other hand, several experiments [5, 6] do show 2CK signatures [7, 8]. However, the realization of the 2CK effect within the usual scenario of a heavy par-

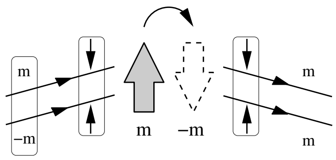

Figure 1 Pair breaking due to a pseudo spin flip process.

ticle tunneling in a double-well potential has recently been called into question by the prediction of an exceedingly low Kondo temperature T_K [9] due to a cancellation of particle and hole contributions under the assumption of complete particle-hole symmetry even at high energies.

In this situation it is important to search for unambiguous experimental signatures that identify TLS in metals. In the present note we propose to consider the pair breaking effect of 2CK impurities in an s-wave superconductor. A single 2CK impurity in a normal-superconducting junction has been considered previously [10], but the effect of a finite 2CK impurity density on the superconducting order parameter is poorly understood. As a realization of a TLS we here consider an atom or molecule with a rotational degree of freedom. Note that the magnetic response in certain glasses has been successfully explained by the rotational motion of TLS [11]. In this case, the impurity angular momentum states $\ell = 0$ and $\ell > 0$, $m = 0$ of the impurity might be blocked by the shape of the confining potential as considered in [11]. The ground state is then doubly degenerate ($\ell = 1$, $m = \pm 1$), protected by time reversal symmetry, which will lead to a 2CK effect, when coupled to the conduction electron continuum.

We employ the standard BCS Hamiltonian to describe the s-wave superconductor and the two-channel Anderson-Impurity model in auxiliary particle representation [12] for the localized dynamical defect, $H = H_o + H_{BCS} + H_{imp}$, with

$$\begin{aligned} H_o &= \sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} \ , \quad H_{BCS} = -\sum_{\sigma} \Delta_\sigma \sum_{\mathbf{k}} \left(c^\dagger_{-\mathbf{k}-\sigma} c^\dagger_{\mathbf{k}\sigma} + c_{\mathbf{k}\sigma} c_{-\mathbf{k}-\sigma} \right), \\ H_{imp} &= \sum_i \sum_{m=\pm 1} \epsilon_d f^\dagger_m f_m + V \sum_i^N \sum_{\sigma,m} \left(c^\dagger_{i\sigma m} b^\dagger_{-\sigma} f_m + f^\dagger_m b_{-\sigma} c_{i\sigma m} \right), \quad (1.1) \end{aligned}$$

where $c^\dagger_{i\sigma m}$ creates a conduction electron with spin σ and pseudospin (angular momentum quantum number) $m = \pm 1$ centered at the impurity site i, and i runs over all N impurities. $\Delta_\sigma = \lambda \sum_k \langle c_{\mathbf{k}\sigma} c_{-\mathbf{k}-\sigma} \rangle$ ($\lambda =$ BCS coupling const.), and the constraint $Q = \sum_\sigma f^\dagger_\sigma f_\sigma + \sum_m b^\dagger_m b_m = 1$ must be fulfilled at all times. Upon expanding the conduction electron

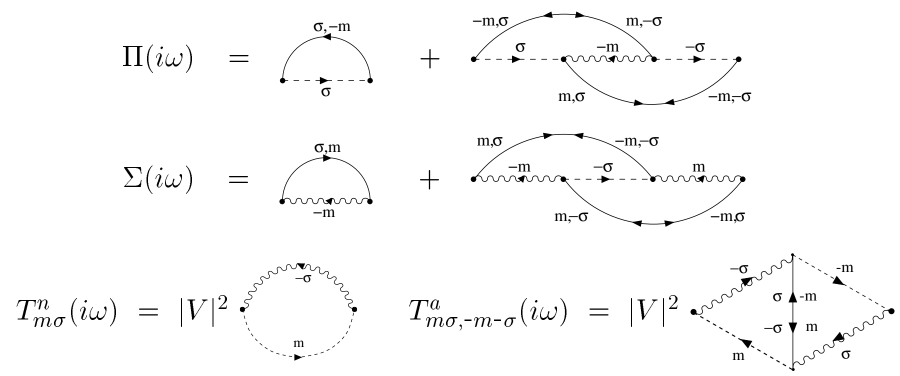

Figure 2 Slave boson and pseudofermion selfenergies, $\Pi(i\omega))$, $\Sigma(i\omega)$, and the normal and anomalous parts of the conduction electron T-matrix, $T^n_{m\sigma}$, $T^a_{m\sigma,-m-\sigma}$. Dashed lines represent pseudo fermion $(-\left\langle T_\tau f_m(\tau) f_m^\dagger \right\rangle)$, wiggly lines slave boson $(-\left\langle T_\tau b_\sigma(\tau) b_\sigma^\dagger \right\rangle)$, and the solid line the conduction electron propagators.

operator $\psi_\sigma(\mathbf{r}) = \sum_\mathbf{k} c_{\mathbf{k}\sigma} e^{i\mathbf{kr}}$ in terms of spherical harmonics $Y_{\ell m}(\hat{\mathbf{r}})$ around the impurity site, $\psi_\sigma(\mathbf{r}) = \frac{1}{r} \sum\limits_{l=0}^{\infty} \sum\limits_{m=-\ell}^{\ell} a_{\ell m\sigma}(r) Y_{\ell m}(\hat{\mathbf{r}})$, the BCS term of the Hamiltonian takes the form

$$H_{BCS} = -\sum_\sigma \Delta_\sigma \sum_{\ell m} \int_0^\infty dk (-1)^{l+m} \left(a^\dagger_{\ell-m-\sigma}(k) a^\dagger_{\ell m\sigma}(k) + h.c. \right), \quad (1.2)$$

with $\Delta_\sigma = \lambda \sum_{\ell m} \int_0^\infty dk (-1)^{l+m} \langle a_{\ell m\sigma}(k) a_{\ell-m-\sigma}(k) \rangle$. It is seen that the 2CK interaction H_{imp} breaks Cooper pairs in the space of pseudospin m, as visualized in Fig. 1, analogous to the pair breaking effect of magnetic impurities [13, 14]. However, unlike a magnetic single channel spin, the pseudospin is not screened by the 2CK effect at low T [4] and pairbreaking occurs even when $T_K \gg T_{co}$, where T_{co} is the BCS transition temperature.

Physical properties are calculated within the scheme of a Φ-derivable theory, defined diagrammatically in Fig. 2. The first column of diagrams represents the non-crossing approximation (NCA), which is known to correctly describe the low T behavior of 2CK impurities [12]. We follow Ref. [15] in extending the NCA to include coupling between the superconductor and the 2CK defects (Fig. 2, second column). The pairbreaking effect is expressed in these terms by the coupling of different Nambu sectors of the Hilbert space in the intermediate states. Note that these terms carry a relative sign compared to the magnetic case [15] because Δ_σ changes sign under reversal of the magnetic spin but not of the pseudospin[10], as follows from the definition of Δ_σ. Fig. 3 shows for the case of magnetic 2CK impurities the conduction electron density of states for various impurity concentrations. The results for the case of non-magnetic 2CK defects will be published elsewhere.

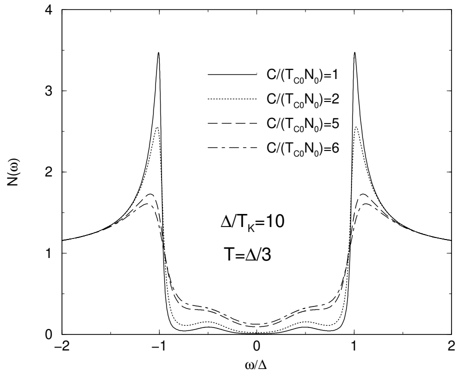

Figure 3 Density of states for different impurity concentrations $C/T_{co}N_o$.

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