Literatura

[1] K. G. Wilson, *The renormalization group: Critical phenomena and the Kondo problem*, Rev. Mod. Phys. **47**, 4 (1975).

[2] H. R. Krishna-Murphy, J. W. Wilkins, K. G. Wilson, *Renormalization-group approach to the Anderson model of dilute magnetic alloys. I. Static properties for the symmetric case*, Phys. Rev. B **21**, 1003 (1980).

[3] H. R. Krishna-Murphy, J. W. Wilkins, K. G. Wilson, *Renormalization-group approach to the Anderson model of dilute magnetic alloys. II. Static properties for the asymmetric case*, Phys. Rev. B **21**, 1044 (1980).

Krzysiek Wójcik, Bukowina Tatrzańska
5.07.2013, Efekt Kondo

Układ, 4 stany:

$|0\rangle$ – puste pudełko

$|\uparrow\rangle$ – pudełko, e^- ze spinem $\uparrow$

$|\downarrow\rangle$ – ——"—— $\downarrow$

$|2\rangle$ – pudełko, 2 e^- z przeciwnymi spinami (całkowity spin = 0)

stan pudełka: $|\Psi\rangle = \alpha_0|0\rangle + \alpha_\uparrow|\uparrow\rangle + \ldots$

$\alpha_i \in \mathbb{C}$, $\sum_i |\alpha_i|^2 = 1$, $|\alpha_i|^2$ – prawdopodobieństwo stanu $|i\rangle$

$d_\uparrow^+|0\rangle = |\uparrow\rangle$

$d_\uparrow^+|\downarrow\rangle = |2\rangle$ $\qquad d_\sigma d_{\sigma'}^+ = -d_{\sigma'}^+ d_\sigma$

$d_\uparrow^+|\uparrow\rangle = 0$ $\qquad d_\uparrow^+ d_\uparrow$ – operator liczby cząstek

$d_\uparrow^+|2\rangle = 0$ $\qquad d_\uparrow^+ d_\uparrow |2\rangle = 1|2\rangle$

$(d_\uparrow^+ d_\uparrow + d_\downarrow^+ d_\downarrow)|2\rangle = 2|2\rangle$ $\qquad d_\uparrow^+ d_\uparrow = 1 - d_\uparrow d_\uparrow^+$

$H = \sum_\sigma \varepsilon_d d_\sigma^+ d_\sigma$, $\sigma \in \{\uparrow, \downarrow\}$ $\qquad$ L1

$\langle\uparrow|H|\uparrow\rangle = \langle\uparrow|\varepsilon_d|\uparrow\rangle = \varepsilon_d$

$\langle 2|H|2\rangle = 2\varepsilon_d$

0

ε_d $\qquad \varepsilon_d < 0$

$\langle 2|2\rangle = ?$ $\quad \langle 0|d_\downarrow \underbrace{d_\uparrow d_\uparrow^+}_{1-\cancel{d_\uparrow^+ d_\uparrow}} d_\downarrow^+|0\rangle = \langle 0|\underbrace{d_\downarrow d_\downarrow^+}_{1-\cancel{d_\downarrow^+ d_\downarrow}}|0\rangle = 1$

$\sum_{s_1,s_2} d_{s_1}^+ d_{s_2}^+ \varphi_{s_1,s_2}|0\rangle =$

$\varphi_{s_1,s_2} = \frac{i}{2}\sigma_{2\,s_1,s_2}$

$|x\rangle = d_\uparrow^+ d_\downarrow^+|0\rangle =$ $\quad \sigma_y = \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$

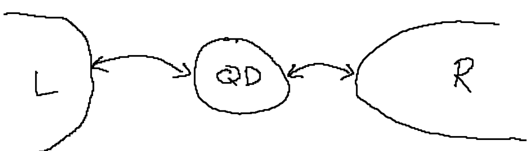
$\sigma_{s_1 s_2}$ = elementy macierzy Pauliego

$H = \sum_\sigma \varepsilon_d d_\sigma^+ d_\sigma + U d_\uparrow^+ d_\uparrow d_\downarrow^+ d_\downarrow$, $U > 0$

$\langle\uparrow|H|\uparrow\rangle = \varepsilon_d$ $\qquad \varepsilon_d + U$

$\langle 2|H|2\rangle = 2\varepsilon_d + U$ $\qquad 0$

$= \varepsilon_d + (\varepsilon_d + U)$ $\qquad \varepsilon_d$



$H = \sum_\sigma \varepsilon_d d_\sigma^+ d_\sigma + U d_\uparrow^+ d_\uparrow d_\downarrow^+ d_\downarrow$

$+ \sum_{\substack{r \in \{L,R\} \\ r,\bar{k},\sigma}} \varepsilon_{\bar{k}} c_{r\bar{k}\sigma}^+ c_{r\bar{k}\sigma}$

$+ \sum_{r,\bar{k},\sigma} \frac{h_{r\bar{k}\sigma}}{\sqrt{N_r}} (c_{r\bar{k}\sigma}^+ d_\sigma + h.c.)$

tw. Blocha: $\psi(\bar{x}) = e^{i\bar{k}\bar{x}} u(\bar{x})$

ψ w potencjale periodycznym; u ma symetrię potencjału

$\bar{k} \in$ pierwsza strefa Brillouina

1D $\to$ $k \in [-\frac{\pi}{a}, \frac{\pi}{a}]$

L2

$\leftarrow$ schemat układu doświadczalnego

1) pomijamy strefy Brillouina inne niż pierwsza

2) zakładamy sferyczną symetrię I strefy B.

3) zakładamy, że $\varepsilon_{\bar{k}} = \varepsilon(|\bar{k}|)$

4) $\bar{k} \to k, l, m$; $h_{r\bar{k}\sigma} \to h_{klm}$

zakładamy, że $h_{r\bar{k}\sigma}$ nie zależy od r i σ

oraz że $h_{klm} = 0$ dla $l > 0$ (dla wszystkich k)

5) $\sum_{\vec{k}} \to \sum_{k,l,m} \to \int k^2 dk \cdot \frac{N_e}{\vartheta} 4\pi \to \int d\varepsilon$

6) $\rho(\varepsilon) = \sum_{\vec{k}} \delta(\varepsilon - \varepsilon_{\vec{k}}) = \frac{4\pi}{\vartheta} k^2 \frac{dk}{d\varepsilon}$

$\rho(\varepsilon) = \text{const.}$

7) $h_k = \begin{cases} h & -D < \varepsilon < D \\ 0 & \end{cases} \qquad (E_F = 0)$

$$H = \sum_\sigma \varepsilon_d d_\sigma^\dagger d_\sigma + U d_\uparrow^\dagger d_\uparrow d_\downarrow^\dagger d_\downarrow + \sum_{r\sigma} \int_{-D}^{D} d\varepsilon\, \varepsilon\, c_{r\varepsilon\sigma}^\dagger c_{r\varepsilon\sigma}$$
$$+ \sum_{r\sigma} \int_{-D}^{D} d\varepsilon\, \sqrt{\rho h^2}\, (c_{r\varepsilon\sigma}^\dagger d_\sigma + h.c.)$$
$$+ \text{diagonalne}$$

$$C_{\pm\varepsilon\sigma} = \frac{1}{\sqrt{2}}(c_{R\varepsilon\sigma} \pm c_{L\varepsilon\sigma})$$

C_- się nie sprzęgają do QD

L3

$-1 \quad -\Lambda^{-1} \quad -\Lambda^{-2} \quad 0 \quad \Lambda^{-2} \quad \Lambda^{-1} \quad 1$ $\qquad I_0^- \qquad I_0^+$

$D = 1$

$$I_n^{\pm} = \pm[\Lambda^{-(n+1)}, \Lambda^{-n}]$$

Λ – niefizyczny parametr, $\Lambda > 1$

$$c_{r\varepsilon\sigma}^\dagger \to c_{\pm nl\sigma}^\dagger = \int_{-D}^{D} \psi_{nl}^{\pm}(\varepsilon)\, c_{+\varepsilon\sigma}^\dagger\, d\varepsilon$$

$$\psi_{nl}^{\pm} = \begin{cases} N_n e^{i\omega_n l \varepsilon} & \varepsilon \in I_n^{\pm} \\ 0 & \text{w.p.p.} \end{cases}$$

$$\omega_n = \frac{2\pi}{\Lambda^{-n} - \Lambda^{-n-1}}$$

pominiemy stany z $l \neq 0$

Zmiana bazy ↷ $\quad d \quad f_0 \quad f_1 \quad \dots \quad f_n \quad \dots$

$$H = \sum_\sigma \varepsilon_d d_\sigma^\dagger d_\sigma + U d_\uparrow^\dagger d_\uparrow d_\downarrow^\dagger d_\downarrow$$
$$+ \frac{1}{2}(1 + \Lambda^{-1}) \sum_{n\sigma} \Lambda^{-n/2} \xi_n (f_{n\sigma}^\dagger f_{n+1\sigma} + h.c.)$$
$$+ \sum_\sigma \sqrt{2\rho h^2}\, (f_{0\sigma}^\dagger d_\sigma + h.c.)$$

$$\xi_n = \frac{1 - \Lambda^{-n-1}}{(1 - \Lambda^{-2n-1})^{1/2} (1 - \Lambda^{-2n-3})^{1/2}} \sim 1$$

$H_N = \Lambda^{(N-1)/2} \cdot (H$, w którym suma po n przebiega do N zamiast do $\infty)$

$$H_{N+1} = \Lambda^{1/2} H_N + \sum_\sigma \tilde{\xi}_N (f_{N\sigma}^\dagger f_{N+1\sigma} + h.c.)$$

$$H = \lim_{N \to \infty} \Lambda^{-(N-1)/2} H_N$$

L4

Procedura rozwiązywania H:

1) Rozwiązujemy H_0

2) Konstruujemy H_1, rozw. H_1

...

3) Wybieramy stany nisko-energetyczne i z nich konstruujemy H_{N+1}

$$H_5 = \begin{pmatrix} 0 & \alpha \\ \alpha & 1 \end{pmatrix} = |v_1\rangle \varepsilon_1 \langle v_1| + |v_2\rangle \varepsilon_2 \langle v_2|$$
$$\varepsilon_1 = \frac{1}{2} - \frac{1}{2}\sqrt{1+\alpha^2} \qquad \varepsilon_2 = \frac{1}{2} + \frac{1}{2}\sqrt{1+\alpha^2}$$

$$H_6 = \Lambda^{1/2} H_5 + \xi_6 (|3\rangle\langle 2| + |2\rangle\langle 3|)$$
$$|2\rangle = \beta_1 |v_1\rangle + \beta_2 |v_2\rangle \approx \beta_1 |v_1\rangle$$

Wyniki moich rachunków: