Quantum phase transition between one-channel and two-channel Kondo polarons

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Motivation

Dilute particles moving in quantum liquids: New physics?

-) Charge carriers in weakly doped semiconductors or Mott insulators
   -) Ions in $^3$He
   -) Muons in metals
   -) Electrons in multi-band quantum wires
-) Multi-component ultracold gases with strong population imbalance

A. Rosch, Adv. Phys. 48, 295 (1999)
S. Palzer et al., Phys. Rev. Lett. 103, 150601 (2009)
Chikkatur, Gorlitz, Stamper-Kurn, Inouye, Gupta and Ketterle, PRL 85, 483 (2000)
I. Bloch, J. Dalibard and W. Zwerger, RMP 80, 885 (2008)
In conclusion, we have studied a novel class of mobile impurity dynamics (Infrared Dynamics, ort catastrophe) in a general 1D quantum liquid (Bose-Hubbard model, no spin fluctuations), as well as the conditions for its breakdown and the reemergence of quasiparticle behavior.

– Yasuyuki Kato, K. A. Al-Hassanieh, A. E. Feiguin, Eddy Timmermans and C. D. Batista

**Novel polaron state for single impurity in a bosonic Mott insulator**

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cold atoms, two species, qp with effective mass, transition to a deconfined state with parameters and other papers on mobile non-magnetic impurities coupled to interacting 1D bosons
Mobile impurity model (1D)

\[ \mathcal{H} = \sum_{i=1}^{L} \sum_{\sigma} \left( -t c_{i\sigma}^\dagger c_{i+1\sigma} - t' d_{i\sigma}^\dagger d_{i+1\sigma} + h.c. \right) \]

\[ + \sum_{i=1}^{L} \left( J \vec{S}_i \cdot \vec{s}_i + V N_i n_i + h S_i^z \right) \]

\( J > 0 \) (AF)

\[ \sigma_i \quad c_i \quad d_i \]

\[ J \quad t' \quad t \]

\( c \) particles

\( d \) particles
Impurity scattering in 1D Fermi gas

- Low energy scattering near Fermi points
  - Momentum transfers multiples of $2p_F$

- Characteristic scale
  \[ E_{\text{recoil}} \equiv \frac{2p_F^2}{M} \]

- For $k_B T \ll E_{\text{recoil}}$ such processes frozen out

- Forward scattering dominates at low temperatures

$t'=0$ only even modes couple (1CK, FL). Finite $t'$: symmetry breaks $\rightarrow$ 2CK, NFL
1CK: X. Wang, Mod. Phys. Lett. B 12, 667 (1998) using DMRG
(De)Localization effects (OBC)

\[ J = 6 \]

\[ L = 11 \text{ and } 41 \]
Localization/Delocalization

To find a length-independent transition we will use PBC
Ground-state phase diagram
\[ M = \frac{1}{L} \sum_{i=1}^{L} \langle \psi_0(h) | S_i^z | \psi_0(h) \rangle \]
One and two-channel Kondo physics

\[ \Delta = \frac{2\pi}{L} \]
\[ \Gamma \sim \frac{1}{T_K} \]

\[ \chi_{1\text{CK}} = \frac{2\pi^2 \Gamma + \Delta_L}{2(\pi^2 \Gamma + \Delta_L)^2} \]

\[ \chi_{2\text{CK}} = \frac{1}{2(\Delta_L + 4\pi^2 \Gamma)} \ln \left[ 1 + \frac{4\Gamma \Delta_L + (4\pi \Gamma)^2}{\Delta_L^2} \right] \]

Log divergence for \( L \rightarrow \infty \)

G. Zarand, J. von Delft, Phys. Rev. B 61, 6918 (2000).
P. D. Sacramento, P. Schlottmann, Phys. Rev. B 43, 13294 (1991).
$J=5$

(a) 

(b) 

(c) 

$\chi/\chi_L=5$

$1/L$
Scaling and universality:

\[ \chi(t', J), \Delta_L(t', J) / \Gamma(t', J) \]
All points

\[ \chi \Gamma(t', J) \]

\[ \Delta_L(t', J) / \Gamma(t', J) \]

1CK

2CK; 5x
- for $t' = 0$ $b = \Delta_L$ decreases monotonically from $4\pi$
Main physics and conclusions

- **Weak-coupling limit:** $T^0_K < t' < t$. The motion of the Kondo cloud renders the 1CK effect unstable, such that left-and right-moving $c$ fermions form two separate screening channels for the impurity spin.

- **Strong-coupling limit:** $J > t > t'$. In limit $J \to \infty$ the impurity locks into a singlet with one $c$ electron. For $t' = 0$ this singlet is immobile. From 1st order perturbation theory in $t'$ the singlet forms a Bloch wave with a kinetic energy of order $t'$. This corresponds to a slowly moving 1CK polaron of minimal size.

- **Strong-coupling limit:** $J > t' > t$. Whereas for $t'/t \to 0$ the $c$ electrons simply adjust to the position of the singlet. For a faster polaron, which is only possible along a sequence of singly occupied $c$ sites, the $c$ electron kinetic energy will be quenched in a vicinity of size $\xi_c$ of the impurity.

- **Nagaoka limit:** $t = 0$. While the spin alignment on the $c$ sites can be arbitrary for $J = \infty$, ferromagnetic alignment is preferred for any finite $t'/J$ – this kinetic magnetism can be understood as double-exchange or Nagaoka ferromagnetism.
