Two Rydberg-dressed atoms escaping from an open well

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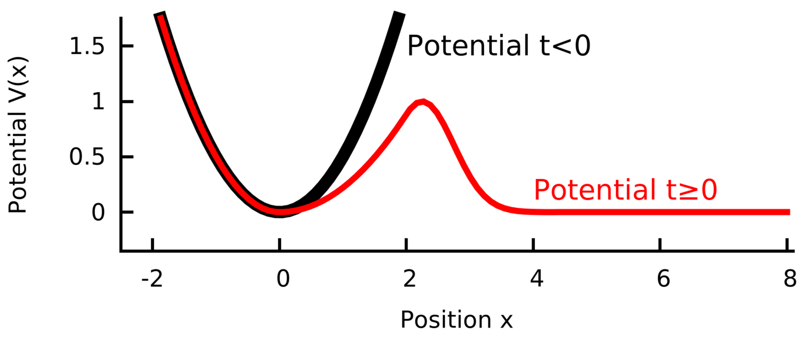
Abstract

We analyze the dynamics of two Rydberg-dressed particles (bosons or fermions) tunneling from a potential well into open space. Significant differences occur between the decay dynamics of bosons and fermions — for the fermionic system much stronger attractive interactions are needed to achieve pair tunneling, and tuning the interaction range modifies the decay process in opposite ways for fermions and bosons. We also show that for sufficiently strong attractive interactions, the dominant decay mechanism switches from sequential tunneling to pair tunneling; the required critical value of interaction strength can be modified by tuning the interaction range. In light of recent experimental realizations of Rydberg dressing of atoms, and tunneling few-body systems, these results offer promise for future experiments.

The model

$$H = \sum_{i=1}^{2}\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_i^2} + V(x_i)\right] + U(x_1 - x_2)$$

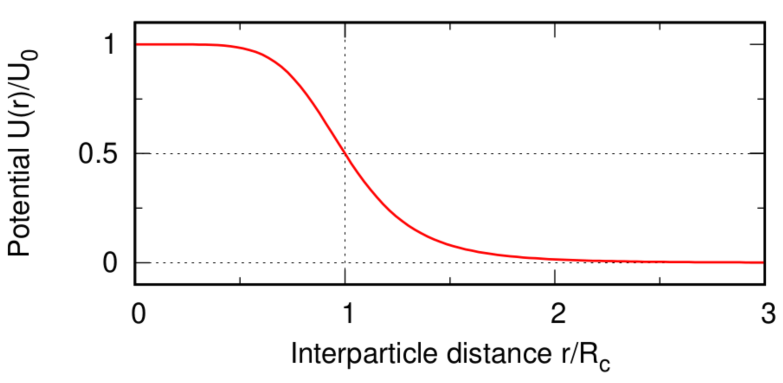


The setup: Initial state is the harmonic oscillator ground state of two identical particles (bosons or fermions) interacting via *U(r)*

At $t = 0$ the trap is suddenly opened and the particles can tunnel into open space

$$U(r) = \frac{g}{2R_c}\left[1 + \left(\frac{r}{R_c}\right)^6\right]^{-1}$$

The interaction: The effective interaction between two atoms in "Rydberg-dressed" states can be modelled with the potential *U(r)*



The interaction range R_c and amplitude $g/2R_c$ can be regulated experimentally

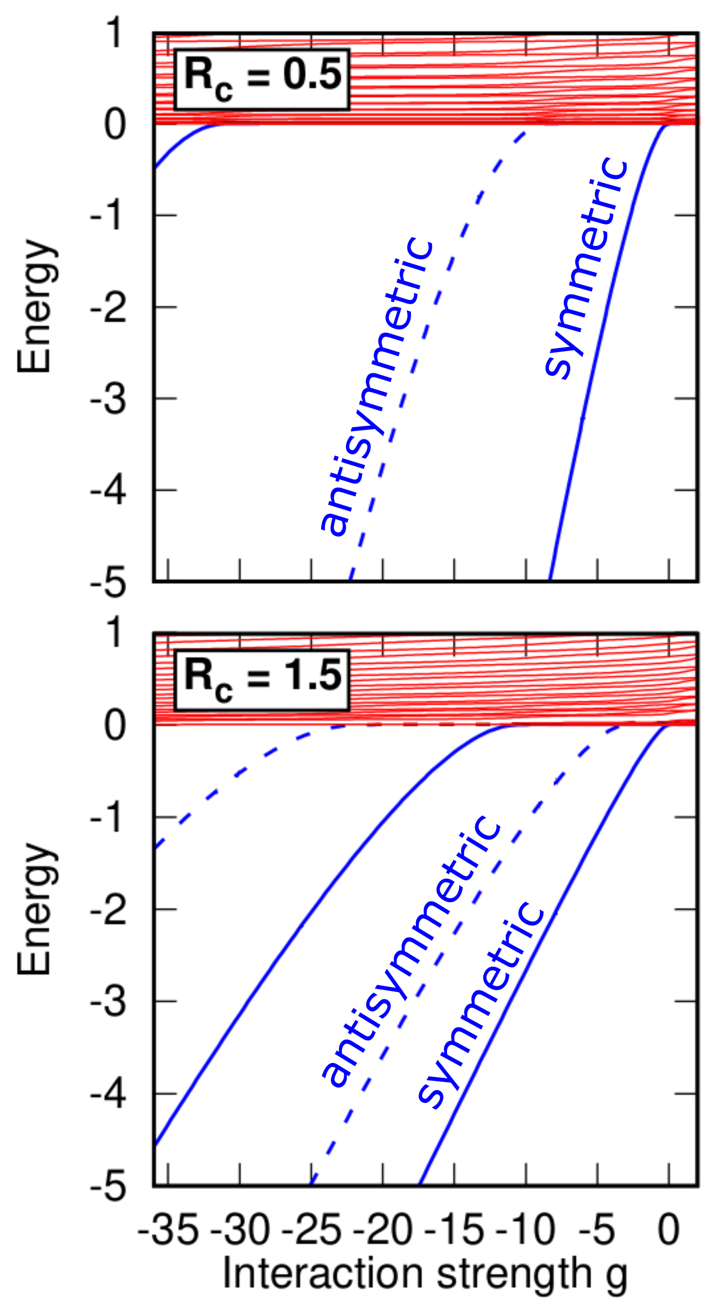
In the zero-range limit, *U(r)* is almost a contact interaction with strength *g*:

$$\lim_{R_c \to 0} U(r) \approx g\delta(r)$$

Relative motion of two particles

$$H_r = -\frac{\partial^2}{\partial r^2} + U(r)$$

Relative motion Hamiltonian spectrum: Relative-motion eigenstates of two particles fall into two groups: states describing two free particles (marked in red) or a bound pair (blue). The availability of the bound pair states depends on the interaction parameters



Significance of quantum statistics:

A state of two bound particles that is *symmetric* under particle exchange exists for any *g < 0*. Therefore, ***bosons*** can tunnel as bound pairs for any attractive interaction *g < 0*

An *antisymmetric* bound state becomes available only at $g < g_{pair}$ (g_{pair} depends on R_c). Therefore, ***fermions*** can tunnel as pairs only for sufficiently strong attractions $|g| > |g_{pair}|$

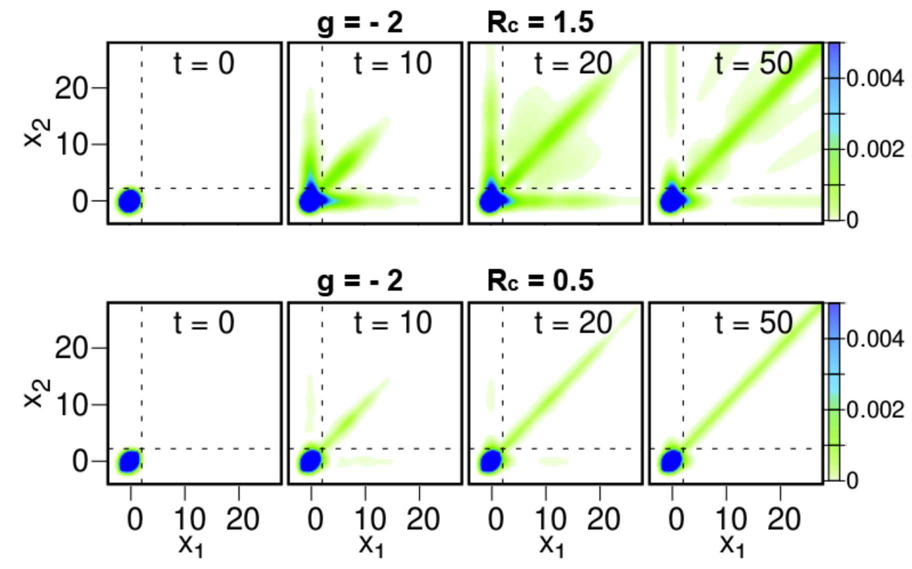
Behavior in the zero-range limit

Bosons: Since the interaction amplitude is $\sim 1/R_c$, the interaction at a given *g* becomes *stronger* as interaction range approaches zero.

Fermions: At zero interaction range, identical fermions do not feel the interaction at all. Thus, the interaction at a given *g* becomes *weaker* as R_c approaches zero.

Two-boson dynamics

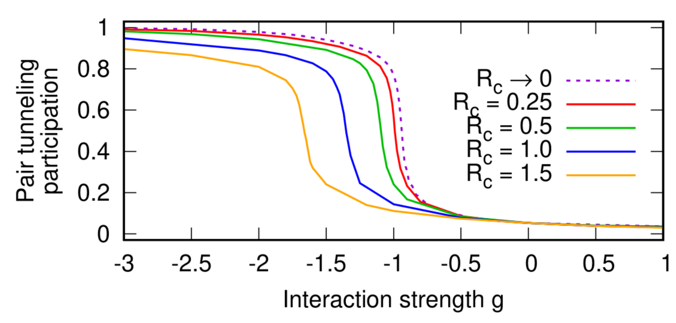
Probability density: Probability of finding the two bosons at positions x_1,x_2 at time *t*



For *g < 0* both sequential and pair tunneling can occur

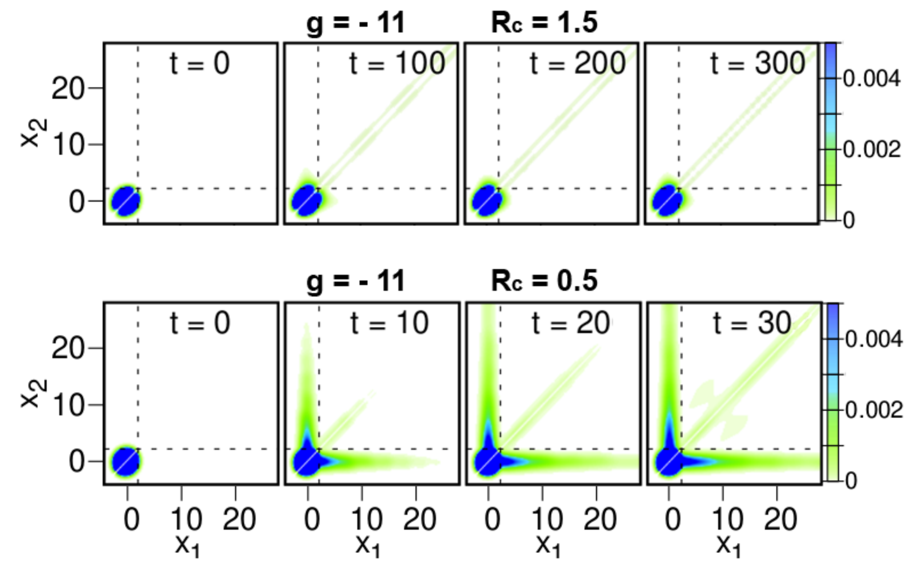
When the interaction range decreases, attractions become stronger and pair tunneling is favored

Relative participation of pair tunneling vs. sequential tunneling: Found by analyzing the flux of probability density through the barrier

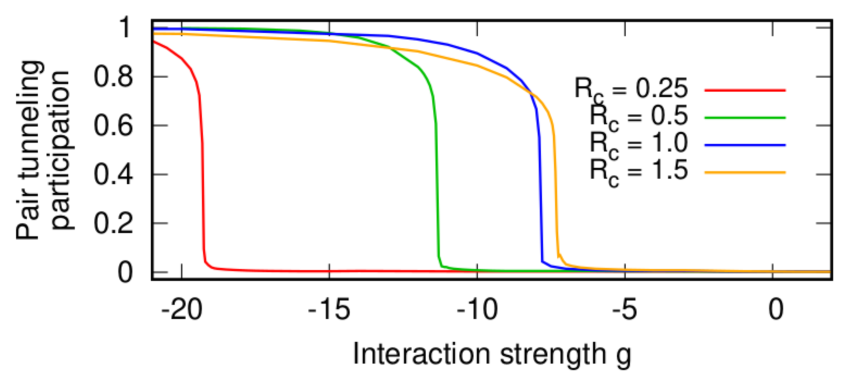


At sufficiently strong attractions, sequential tunneling is suppressed and pair tunneling becomes dominant.
For smaller R_C, a smaller interaction strength is needed to suppress sequential tunneling

Two-fermion dynamics

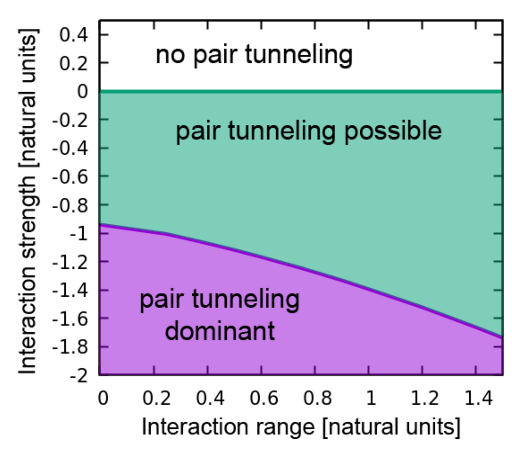


The behavior for fermions is opposite from bosons:
When the interaction range decreases, attractions become weaker and sequential tunneling is less suppressed

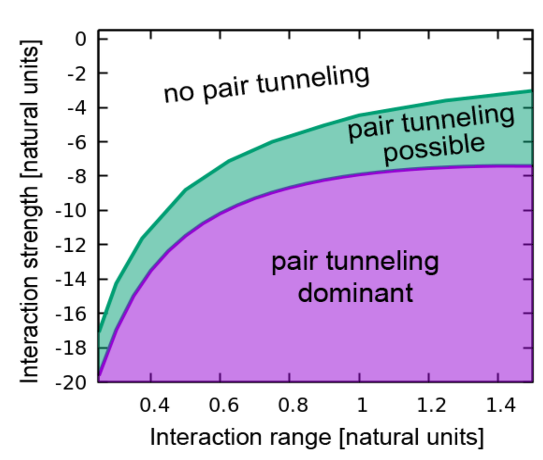


Availability of tunneling processes

Bosons



Fermions



Summary

- The tunneling of two particles can be described in terms of two distinct decay channels (sequential/pair tunneling)
- Tuning the interaction parameters affects the participation of different decay channels
- Changing the range of the interaction affects bosons and fermions in quite opposite ways

More details:
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