Decoherence in a bosonic Josephson junction

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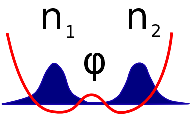
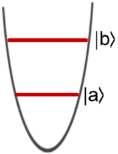
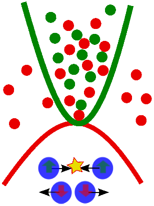
Outline





- Motivation
- N particles in two modes

- 'Typical' evolution - creation of entanglement



- Effect of particle losses

Motivation

'better' statistics = with uncertainties smaller than shot noise

NEEDED:
entangled states
limits due to decoherence and dephasing
here: effect of particle losses

Initial states

$$|\phi = 0\rangle = \left(\frac{\hat{a}^\dagger + \hat{b}^\dagger}{\sqrt{2}}\right)^N |0\rangle = \sum_{n=0}^N \sqrt{\frac{1}{2^N}\binom{N}{n}}\,|n, N-n\rangle$$

Initial states

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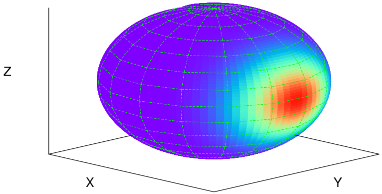
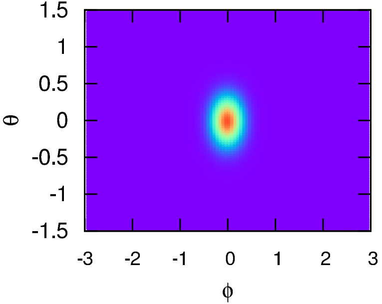




$$\hat{S}_z = (\hat{n}_a - \hat{n}_b)/2$$

Evolution

Hamiltonian (**no tunneling**):

$$\begin{aligned}\hat{H} &= \frac{\chi_a}{2}\left(a^\dagger a^\dagger a a\right) + \chi_{ab}\left(a^\dagger a b^\dagger b\right) + \frac{\chi_b}{2}\left(b^\dagger b^\dagger b b\right) = \\ &= \chi \hat{S}_z^2 + f\left(\hat{N}\right)\end{aligned}$$

If $|\psi\rangle = \sum_{n=0}^{N} c_n |n, N-n\rangle$, then

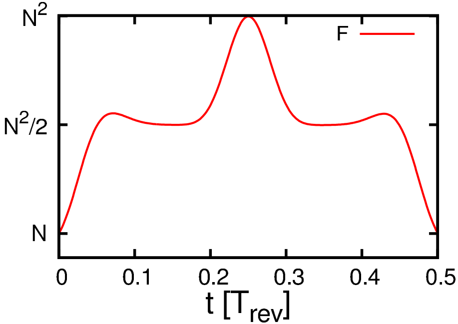
$$\begin{aligned}|\psi(t)\rangle &= \sum_{n=0}^{N} c_n e^{-i(\chi_a - \chi_{ab})\left(a^\dagger a^\dagger a a\right)t} \\ &\quad \times e^{-i(\chi_b - \chi_{ab})\left(b^\dagger b^\dagger b b\right)t} |n, N-n\rangle\end{aligned}$$

Evolution of a coherent state

Fisher information F

$F = F(\hat{\rho})$
$F > N$ - useful entangled state

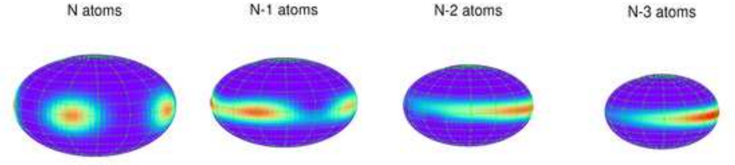
$\max F = N^2$



[1] P. Hyllus *et al.* Phys. Rev. A, **82** (2010) 012337

Particle losses

Bloch sphere?



$$\hat{\rho} = p_N\,\hat{\rho}_N \quad + \quad p_{N-1}\,\hat{\rho}_{N-1} + p_{N-2}\,\hat{\rho}_{N-2} + \;\ldots + p_0\,\hat{\rho}_0$$

Master equation

$$\underbrace{\partial_t \hat{\rho} = -\frac{i}{\hbar}\left[\hat{H}, \hat{\rho}\right]}_{\text{von Neuman equation}} + \underbrace{\mathcal{L}_1 \hat{\rho} + \mathcal{L}_2 \hat{\rho} + \mathcal{L}_3 \hat{\rho}}_{\text{particle losses}},$$

where $\mathcal{L}_n = \mathcal{L}_n^{(a)} + \mathcal{L}_n^{(b)}$

$$\mathcal{L}_n^{(a)} \hat{\rho} = \gamma_n \left[\hat{a}^n, \hat{\rho}\left(\hat{a}^\dagger\right)^n\right] + \gamma_n \left[\hat{a}^n, \hat{\rho}\left(\hat{a}^\dagger\right)^n\right]$$

Exact solution

Master equation

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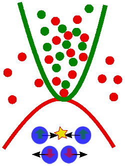
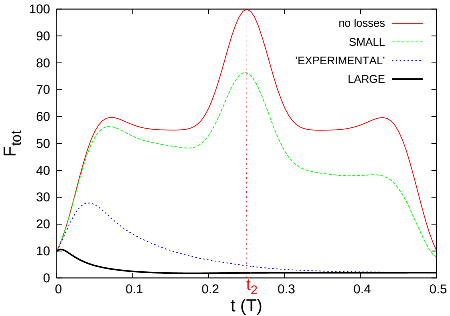
Exact solution

Here: only 2-body losses γ_1, γ_2 - rates of 2−body losses in "a" and "b" mode



Fisher information with losses



From macroscopic to mesoscopic!

Fisher information with losses

number of lost atoms $\sim 20\%$

γ_1, γ_2 - loss rates in the first and the second mode

χ_1, χ_2 - interaction energy of a pair of atoms in the first and the second mode

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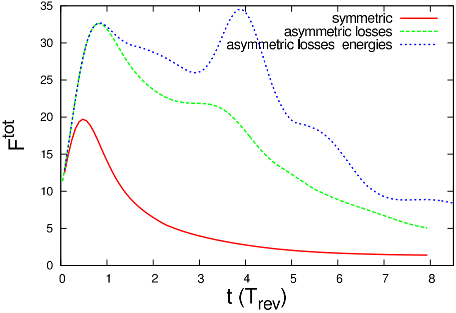


Subspace with N atoms

Case, when no losses occurred
(although they were possible)

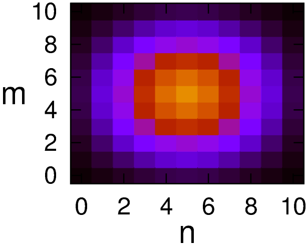
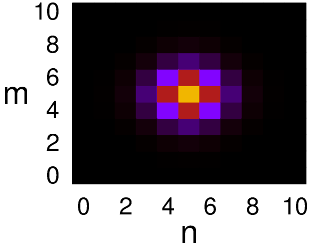
$p(N, t)$ - probability of an loss event at time t in the cloud with initially N atoms
2-body losses

IF $N_1 > N_2$ THEN
$p(N_1, t) > p(N_2, t)$

$|0, N\rangle$ less stable, than $|N/2,\ N/2\rangle$

Do nothing and gain !

$$\langle n, N-n|\hat{\rho}_N|m, N-m\rangle$$

no losses	with 2-body losses
$\hat{\rho}_N^{(0)}$ 	$\hat{\rho}_N^{(0)} e^{-\gamma_2 t\left(\left(n-\frac{N}{2}\right)^2+\left(m-\frac{N}{2}\right)^2\right)}$ 

Final state $= \left|\frac{N}{2}, \frac{N}{2}\right\rangle$ (but with probability $p_N \ll 1$)

process nr 1: 'Gaussian shrinking'

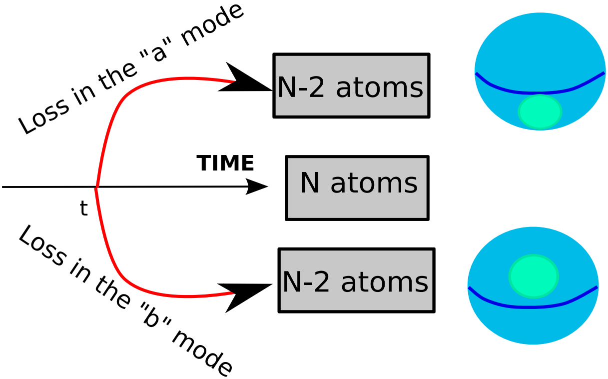
Subspace with $N-2$ atoms

Two body losses only

What happens when **SINGLE** lost event occurred

Subspace with $N-2$ atoms - after one loss event

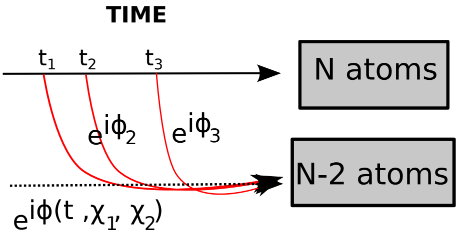
$\hat{S}_z = (\hat{n}_a - \hat{n}_b)/2$

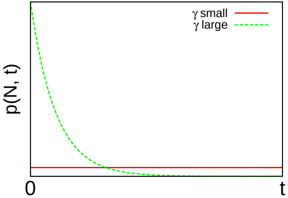


process nr 2: Channeling (with very strong destructive interference for the cat state)

to avoid it: $\gamma_1 \gg \gamma_2$

Subspace with $N-2$ atoms - after one loss event





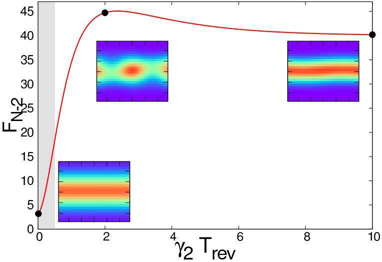
state = incoherent mixture of $|\theta_i, \phi_i\rangle$ $\Delta\phi \propto \frac{\chi}{2\gamma N}$

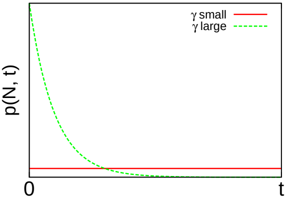
(estimated for small losses)

process nr 3: phase noise

Subspace with $N-2$ atoms - after one loss event

Fixed time ($T_{rev}/2$) but different loss rates

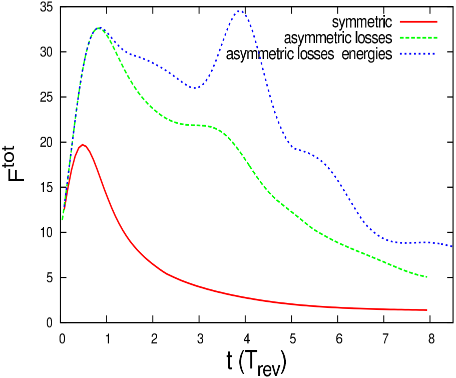




state = incoherent mixture of $|\theta_i, \phi_i\rangle$ $\quad \Delta\phi \propto \frac{\chi}{2\gamma N}$

to avoid it: increase γ or suppress χ

Fisher information with losses



$\gamma_1 = 0$ no channeling

$\gamma_1 = 0$ and $\chi_2 = 0$ no phase noise

subspaces with smaller number of atoms

Summary

1. Exact solution of the master equation
2. Decoherence in subspaces with different number of atoms
   - 'Gaussian shrinking'
   - Phase noise
   - Destructive interference (atoms lost from a or b?)
3. Huge advantage for highly asymmetric losses, using Feshbach resonances
4. Gain via post-selection (?)

TODO-list

- scaling with N
- beyond B-H model
- experimental conditions (phase noise, finite temperature)

Group

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