

Number-phase uncertainty relations and bipartite entanglement detection in spin ensembles

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Outline

1 Motivation

- Why entanglement is important?

2 Spin squeezing and entanglement

- Entanglement
- Collective measurements
- The original spin-squeezing criterion
- Generalized criteria for $j = \frac{1}{2}$, singlet states

3 Detecting multipartite entanglement of Dicke states

- Dicke state realized with a BEC of two-state atoms

4 Detecting bipartite entanglement of Dicke states

- Bipartite entanglement from multipartite entanglement in BEC
- Dicke state in a double well
- Problems to solve in an experiment
- Entanglement detection in Dicke states

Why multipartite entanglement is important?

- Many experiments are aiming to create entangled states with many atoms.
- Full tomography is not possible, we still have to say something meaningful.
- Only collective quantities can be measured.
- Thus, entanglement detection seems to be a good idea ...

Why is this challenging?

- It could happen that
 - it is not possible to create large scale entanglement in a system that is not completely isolated.
 - such entanglement is created, but we cannot verify its presence, since we can measure few things.

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Entanglement

A state is (fully) separable if it can be written as

$$\sum_k p_k \varrho_1^{(k)} \otimes \varrho_2^{(k)} \otimes \dots \otimes \varrho_N^{(k)}.$$

If a state is not separable then it is entangled.

k -producibility/ k -entanglement

A pure state is **k -producible** if it can be written as

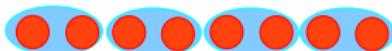
$$|\Phi\rangle = |\Phi_1\rangle \otimes |\Phi_2\rangle \otimes |\Phi_3\rangle \otimes |\Phi_4\rangle \dots$$

where $|\Phi_i\rangle$ are states of at most k qubits.

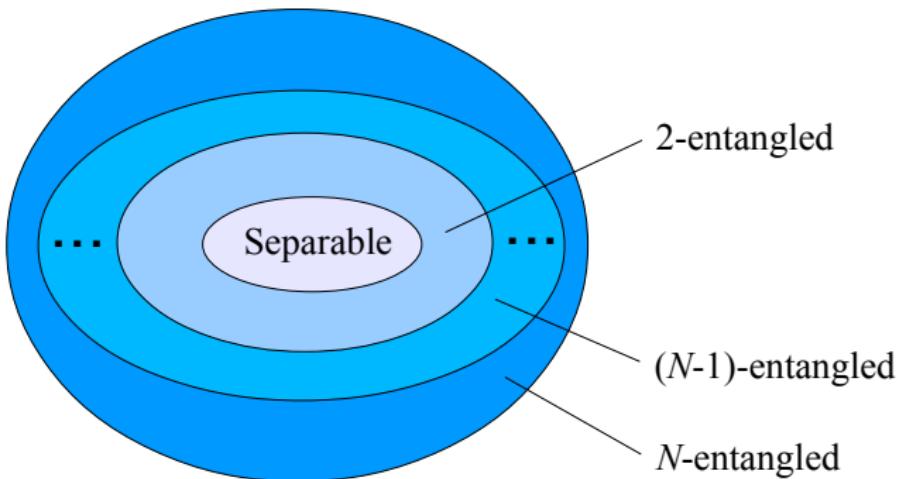
A mixed state is k -producible, if it is a mixture of k -producible pure states.

e.g., O. Guhne and GT, New J. Phys 2005.

- If a state is not k -producible, then it is at least **$(k + 1)$ -particle entangled**.



k -producibility/ k -entanglement II



$(00\rangle + 11\rangle) \otimes (00\rangle + 11\rangle) \otimes (00\rangle + 11\rangle)$	2-entangled
$(000\rangle + 111\rangle) \otimes (000\rangle + 111\rangle)$	3-entangled
$(0000\rangle + 1111\rangle) \otimes (0\rangle + 1\rangle)$	4-entangled

k-entanglement means real *k*-particle quantumness

- *k*-entanglement means that we could not make trivially the experiment from (*k* – 1)-particle experiments.
- The state is not a mixture of product states

$$\varrho_1 \otimes \varrho_2 \otimes \varrho_3 \otimes \dots$$

such that all ϱ_I has at most (*k* – 1) qubits.

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Many-particle systems for $j=1/2$

- For spin- $\frac{1}{2}$ particles, we can measure the **collective angular momentum operators**:

$$J_l := \frac{1}{2} \sum_{k=1}^N \sigma_l^{(k)},$$

where $l = x, y, z$ and $\sigma_l^{(k)}$ a Pauli spin matrices.

- We measure the **expectation values** $\langle J_l \rangle$.
- We can also measure the **variances**

$$(\Delta J_l)^2 := \langle J_l^2 \rangle - \langle J_l \rangle^2.$$

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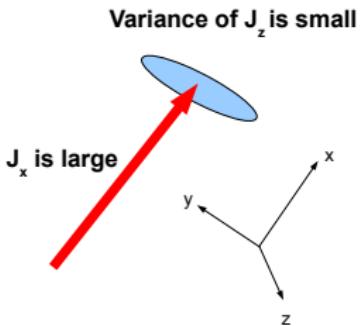
The standard spin-squeezing criterion

The spin squeezing criterion for entanglement detection is

$$\xi_s^2 = N \frac{(\Delta J_z)^2}{\langle J_x \rangle^2 + \langle J_y \rangle^2}.$$

[A. Sørensen, L.M. Duan, J.I. Cirac, P. Zoller, Nature 409, 63 (2001).]

- If $\xi_s^2 < 1$ then the state is entangled.
- States detected are like this:



- They are good for metrology!

Multipartite entanglement in spin squeezing

- We consider pure k -producible states of the form

$$|\Psi\rangle = \otimes_{I=1}^M |\psi_I\rangle,$$

where $|\psi_I\rangle$ is the state of at most k qubits.

Extreme spin squeezing

The spin-squeezing criterion for k -producible states is

$$(\Delta J_z)^2 \geq J_{\max} F_{\frac{k}{2}} \left(\frac{\sqrt{\langle J_x \rangle^2 + \langle J_y \rangle^2}}{J_{\max}} \right),$$

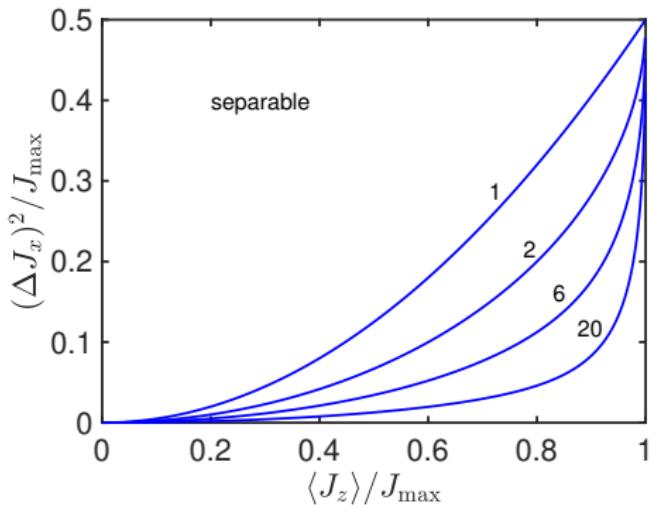
where $J_{\max} = \frac{N}{2}$ and we use the definition

$$F_j(X) := \frac{1}{j} \min_{\substack{\langle j_x \rangle \\ j}} (\Delta j_z)^2.$$

Sørensen and Mølmer, Phys. Rev. Lett. 86, 4431 (2001); experimental test:
Gross, Zibold, Nicklas, Esteve, Oberthaler, Nature 464, 1165 (2010).

Multipartite entanglement in spin squeezing II

- Larger and larger multipartite entanglement is needed to larger and larger squeezing ("extreme spin squeezing").



- $N = 100$ spin-1/2 particles, $J_{\max} = N/2$.

Sørensen and Mølmer, Phys. Rev. Lett. 86, 4431 (2001); experimental test: Gross, Zibold, Nicklas, Esteve, Oberthaler, Nature 464, 1165 (2010).

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Generalized spin squeezing criteria for $j = \frac{1}{2}$

- Let us assume that for a system we know only

$$\vec{J} := (\langle J_x \rangle, \langle J_y \rangle, \langle J_z \rangle),$$

$$\vec{K} := (\langle J_x^2 \rangle, \langle J_y^2 \rangle, \langle J_z^2 \rangle).$$

- Then any state violating the following inequalities is entangled:

$$\langle J_x^2 \rangle + \langle J_y^2 \rangle + \langle J_z^2 \rangle \leq \frac{N(N+2)}{4},$$

$$(\Delta J_x)^2 + (\Delta J_y)^2 + (\Delta J_z)^2 \geq \frac{N}{2}, \quad (\text{singlet states})$$

$$\langle J_k^2 \rangle + \langle J_l^2 \rangle \leq (N-1)(\Delta J_m)^2 + \frac{N}{2}, \quad (\text{Dicke states})$$

$$(N-1) [(\Delta J_k)^2 + (\Delta J_l)^2] \geq \langle J_m^2 \rangle + \frac{N(N-2)}{4},$$

where k, l, m take all the possible permutations of x, y, z .

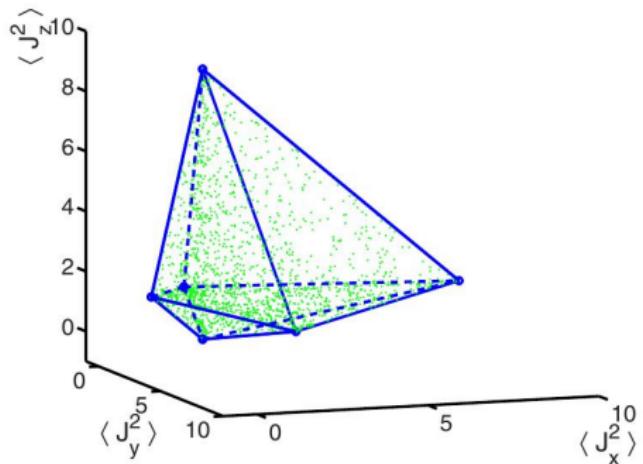
singlets: GT, Phys. Rev. A 69, 052327 (2004);

all Eqs.: GT, C. Knapp, O. Guhne, and H.J. Briegel, PRL 99, 250405 (2007);

spin- j : G. Vitagliano, P. Hyllus, I. L. Egusquiza, GT, PRL 107, 240502 (2011).

Generalized spin squeezing criteria for $j = \frac{1}{2}$ II

- Separable states are in the polytope



- We set $\langle J_l \rangle = 0$ for $l = x, y, z$.

Spin squeezing criteria – Two-particle correlations

All quantities depend only on two-particle correlations

$$\langle J_I \rangle = N \langle j_I \otimes \mathbb{1} \rangle_{\varrho_{2p}}; \quad \langle J_I^2 \rangle = \frac{N}{4} + N(N-1) \langle j_I \otimes j_I \rangle_{\varrho_{2p}}.$$

- Average 2-particle density matrix

$$\varrho_{2p} = \frac{1}{N(N-1)} \sum_{n \neq m} \varrho_{mn}.$$

- We can detect states with a separable ϱ_{2p} !

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$$(N-1)[(\Delta J_k)^2 + (\Delta J_l)^2] \geq \langle J_m^2 \rangle + \frac{N(N-2)}{4},$$

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GT, C. Knapp, O. Gühne, and H.J. Briegel, PRL 99, 250405 (2007);

spin- j : G. Vitagliano, P. Hyllus, I. L. Egusquiza, GT, PRL 107, 240502 (2011).

Dicke states

- Dicke states: eigenstates of $\vec{J}^2 = J_x^2 + J_y^2 + J_z^2$ and J_z .
- Symmetric Dicke states of spin-1/2 particles, with $\langle J_z \rangle = \langle J_z^2 \rangle = 0$

$$|D_N\rangle = \left(\frac{N}{\frac{N}{2}}\right)^{-\frac{1}{2}} \sum_k \mathcal{P}_k \left(|0\rangle^{\otimes \frac{N}{2}} \otimes |1\rangle^{\otimes \frac{N}{2}} \right).$$

Summing over all permutations.

Due to symmetry, $\langle \vec{J}^2 \rangle$ is maximal.

- E.g., for four qubits they look like

$$|D_4\rangle = \frac{1}{\sqrt{6}} (|0011\rangle + |0101\rangle + |1001\rangle + |0110\rangle + |1010\rangle + |1100\rangle).$$

photons: N. Kiesel, C. Schmid, GT, E. Solano, H. Weinfurter, PRL 2007; Prevedel. et al., PRL 2009; W. Wieczorek, R. Krischek, N. Kiesel, P. Michelberger, GT, H. Weinfurter, PRL 2009.

cold atoms: Lücke, Science 2011; Hamley et al, Nat. Phys. 2012.

Dicke states are useful because they ...

- ... possess strong multipartite entanglement, like GHZ states.

GT, JOSAB 2007.

- ... are optimal for quantum metrology, similarly to GHZ states.

Hyllus *et al.*, PRA 2012; Lücke *et al.*, Science 2011;

GT, PRA 2012;

GT and Apellaniz, J. Phys. A, special issue for “50 year of Bell’s theorem”, 2014.

- ... are macroscopically entangled, like GHZ states.

Fröwis, Dür, PRL 2011.

Spin Squeezing Inequality for Dicke states

- Let us rewrite the third inequality. For separable states

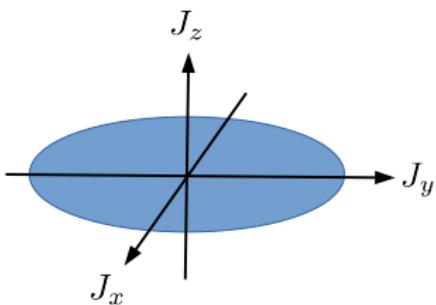
$$\langle J_x^2 \rangle + \langle J_y^2 \rangle - \frac{N}{2} \leq (N-1)(\Delta J_z)^2$$

holds.

- It detects states close to Dicke states since

$$\begin{aligned}\langle J_x^2 + J_y^2 \rangle &= \frac{N}{2} \left(\frac{N}{2} + 1 \right) = \text{max.,} \\ \langle J_z^2 \rangle &= 0.\end{aligned}$$

- "Pancake" like uncertainty ellipse.



Multipartite entanglement around Dicke states

- Measure the same quantities as before

$$(\Delta J_z)^2$$

and

$$\langle J_x^2 + J_y^2 \rangle.$$

- In contrast, for the original spin-squeezing criterion we measured $(\Delta J_z)^2$ and $\langle J_x \rangle^2 + \langle J_y \rangle^2$.
- Pioneering work: linear condition of Luming Duan, Phys. Rev. Lett. (2011). See also Zhang, Duan, New. J. Phys. (2014).

Multipartite entanglement - Our condition

- Sørensen-Mølmer condition for k -producible states

$$(\Delta J_z)^2 \geq J_{\max} F_{\frac{k}{2}} \left(\frac{\sqrt{\langle J_x \rangle^2 + \langle J_y \rangle^2}}{J_{\max}} \right).$$

- Combine it with

$$\langle J_x^2 + J_y^2 \rangle \leq J_{\max} \left(\frac{k}{2} + 1 \right) + \langle J_x \rangle^2 + \langle J_y \rangle^2,$$

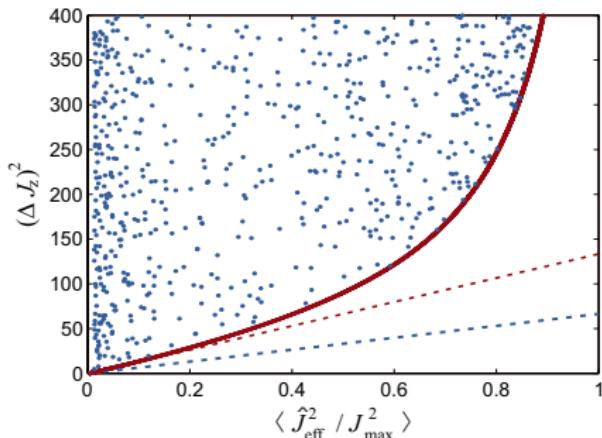
which is true for pure k -producible states. (Remember, $J_{\max} = \frac{N}{2}$.)

Condition for entanglement detection around Dicke states

$$(\Delta J_z)^2 \geq J_{\max} F_{\frac{k}{2}} \left(\frac{\sqrt{\langle J_x^2 + J_y^2 \rangle} - J_{\max} \left(\frac{k}{2} + 1 \right)}{J_{\max}} \right).$$

Due to convexity properties of the expression, this is also valid to mixed separable states.

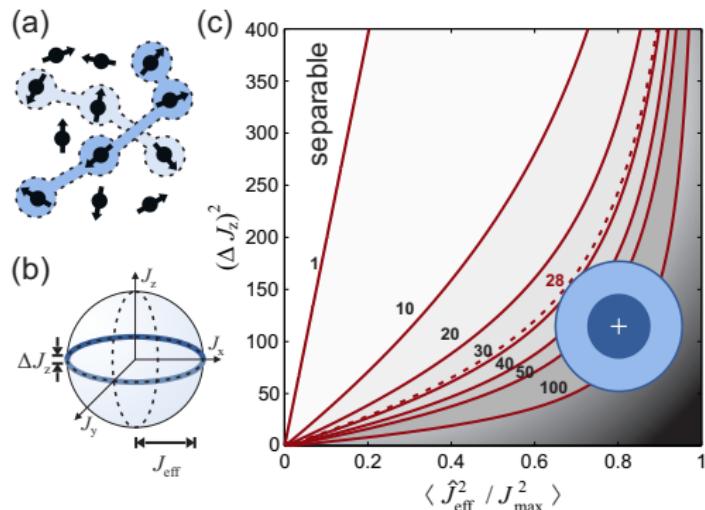
Concrete example



- $N = 8000$ particles, and $J_{\text{eff}} = J_x^2 + J_y^2$.
- Red curve: boundary for 28-particle entanglement.
- Blue dashed line: linear condition given in L.-M. Duan, Phys. Rev. Lett. 107, 180502 (2011).
- Red dashed line: tangent of our curve.

Multipartite entanglement

- Bose-Einstein condensate, 8000 particles. 28-particle entanglement is detected.



$$J_{\text{eff}}^2 = J_x^2 + J_y^2, \quad J_{\text{max}} = \frac{N}{2}.$$

B. Lücke, J. Peise, G. Vitagliano, J. Arlt, L. Santos, GT, and C. Klempert,
PRL 112, 155304 (2014).

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$$\langle J_I \rangle = N \langle j_I \otimes \mathbb{1} \rangle_{\varrho_{2p}}; \quad \langle J_I^2 \rangle = \frac{N}{4} + N(N-1) \langle j_I \otimes j_I \rangle_{\varrho_{2p}}.$$

- Average 2-particle density matrix

$$\varrho_{2p} = \frac{1}{N(N-1)} \sum_{n \neq m} \varrho^{mn}.$$

- We can even detect multipartite entanglement knowing only two-body correlations!

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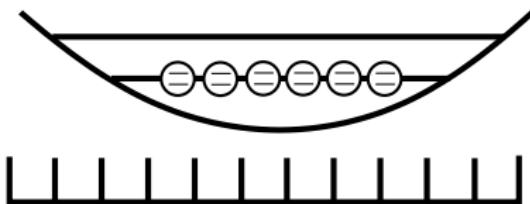
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Bipartite entanglement from bosonic multipartite entanglement

- In the BEC, "all the particles are at the same place."
- In the usual formulation, entanglement is between spatially separated parties.
- Is multipartite entanglement within a BEC useful/real?
- Answer: yes!

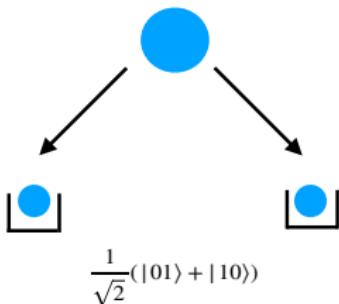
Bipartite entanglement from bosonic multipartite entanglement II

- Dilute cloud argument



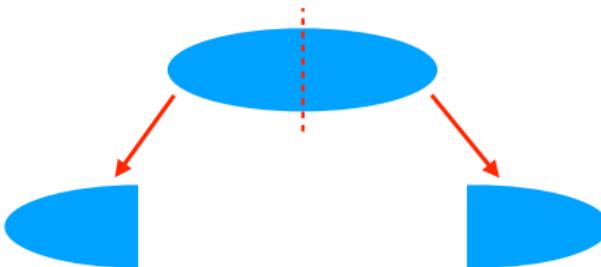
See, e.g., P. Hyllus, L. Pezzé, A Smerzi and GT, PRA 86, 012337 (2012)

$$|n_0 = 1\rangle |n_1 = 1\rangle$$



Bipartite entanglement from bosonic multipartite entanglement III

- After splitting it into two, we have bipartite entanglement if we had before multipartite entanglement.
- The splitting does not generate entanglement, if we consider projecting to a fixed particle number.



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Experiment in the group of Carsten Klempt at the University of Hannover

- Rubidium BEC, spin-1 atoms.
- Initially all atoms in the spin state $|j_z = 0\rangle$.
- Dynamics

$$H = a_0^2 a_{+1}^\dagger a_{-1}^\dagger + (a_0^\dagger)^2 a_{+1} a_{-1}.$$

Tunneling from mode 0 to the mode +1 and -1.

- Understanding the tunneling process

$$\begin{aligned}|j_z = 0\rangle |j_z = 0\rangle &\rightarrow \frac{1}{\sqrt{2}}(|j_z = +1\rangle |j_z = -1\rangle + |j_z = -1\rangle |j_z = +1\rangle) \\&= \text{Dicke state of 2 particles.}\end{aligned}$$

Experiment in the group of Carsten Klempt at the University of Hannover II

- After some time, we have a state

$$|n_0, n_{-1}, n_{+1}\rangle = |N - 2n, n, n\rangle.$$

- That is, $N - 2n$ particles remained in the $|j_z = 0\rangle$ state, while $2n$ particles form a symmetric Dicke state given as

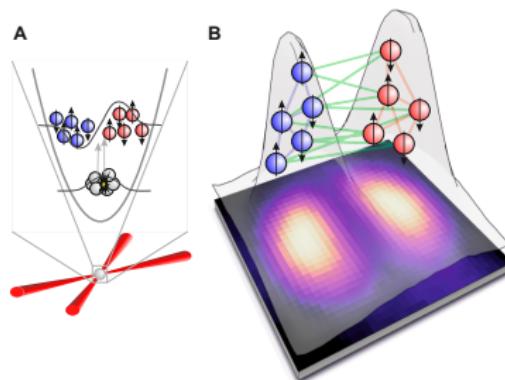
$$|D_N\rangle = \left(\frac{N}{\frac{N}{2}}\right)^{-\frac{1}{2}} \sum_k \mathcal{P}_k \left(|0\rangle^{\otimes \frac{N}{2}} \otimes |1\rangle^{\otimes \frac{N}{2}} \right),$$

where we use $|0\rangle$ and $|1\rangle$ instead of $|j_z = -1\rangle$ and $|j_z = +1\rangle$.

- Half of the atoms in state $|0\rangle$, half of the atoms in state $|1\rangle$ + symmerization.

Experiment in the group of Carsten Klempt at the University of Hannover III

- Important: first excited spatial mode of the trap was used, not the ground state mode.
- It has two "bumps" rather than one, hence they had a split Dicke state.



K. Lange, J. Peise, B. Lücke, I. Kruse, G. Vitagliano, I. Apellaniz, M. Kleinmann, GT, and C. Klempt, Entanglement between two spatially separated atomic modes, Science 360, 416 (2018).

Correlations for Dicke states

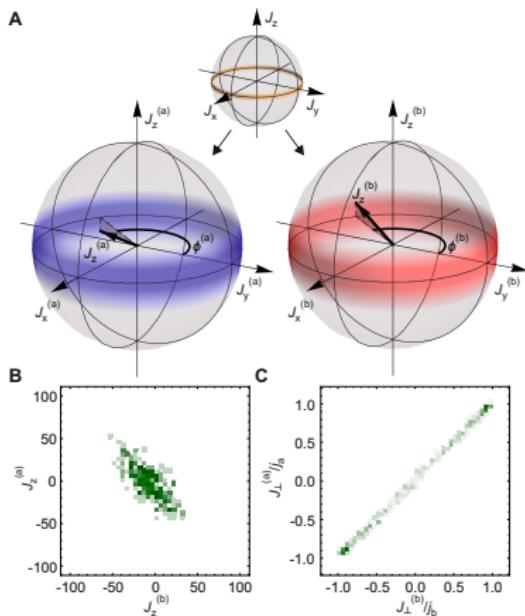
- For the Dicke state

$$\begin{aligned}(\Delta(J_x^a - J_x^b))^2 &\approx 0, \\ (\Delta(J_y^a - J_y^b))^2 &\approx 0, \\ (\Delta J_z)^2 &= 0.\end{aligned}$$

- Measurement results on well "b" can be predicted from measurements on "a"

$$\begin{aligned}J_x^b &\approx J_x^a, \\ J_y^b &\approx J_y^a, \\ J_z^b &= -J_z^a.\end{aligned}$$

Correlations for Dicke states - experimental results



Here, $J_{\perp}^{(n)} = \cos \alpha J_x^{(n)} + \sin \alpha J_y^{(n)}$.

Experiment in [K. Lange et al., Science 334, 773–776 \(2011\)](#).

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Problem 1: Varying particle number

- The experiment is repeated many times. Each time we find a somewhat different particle number.
- Postselecting for a given particle number is not feasible.
- Consider a density matrix

$$\varrho = \sum_{j_a, j_b} Q_{j_a, j_b} \varrho_{j_a, j_b},$$

where ϱ_{j_a, j_b} are states with $2j_a$ and $2j_b$ particles in the two wells, Q_{j_a, j_b} are probabilities.

- ϱ is entangled iff at least one of the ϱ_{j_a, j_b} is entangled.

Problem 1: Varying particle number II

- Even if we have a constant total particle number, the ensemble will not be evenly split.
- Probability distribution for having $N/2 + x$ particles

$$p_x = 2^{-N} \binom{N}{N/2 + x}.$$

- Variance

$$\text{var}(N_a) = \text{var}(x) = \langle x^2 \rangle = \frac{N}{4}.$$

- Collective variance

$$[\Delta(J_I^a - J_I^b)]^2 \approx \sum_{x=-N/2}^{N/2} p_x \left(\frac{N}{8} + \frac{1}{2}x^2 \right) = \frac{N}{8} + \frac{1}{2}\text{var}(x) = \frac{N}{4}, \quad I = x, y.$$

Twice as large due to the unequal splitting.

Problem 1: Varying particle number II

- $N/2 : N/2$ splitting:

$$[\Delta(J_l^a - J_l^b)]^2 = \frac{N}{8}$$

for $l = x, y$.

- Real splitting with partition noise:

$$[\Delta(J_l^a - J_l^b)]^2 \approx \frac{N}{4}.$$

Problem 1: Varying particle number IV

- Let use the normalized quantity mentioned before

$$\mathcal{J}_l^- = \frac{1}{\sqrt{j_a(j_a + 1)}} J_l^a - \frac{1}{\sqrt{j_b(j_b + 1)}} J_l^b$$

for $l = x, y, z$.

- For the variance of \mathcal{J}_l we obtain for $N/2 + x : N/2 - x$ splitting

$$(\Delta \mathcal{J}_l^-)^2 \approx \frac{N}{N^2/2 + 4N - 2x^2}.$$

After splitting $|x| \lesssim \sqrt{N/4}$.

- We have

$$(\Delta \mathcal{J}_l)^2 \approx \frac{2}{N}.$$

$(\Delta \mathcal{J}_l^-)^2$ is not sensitive to the fluctuation of x if N is large.

Problem 2: States are not always symmetric in a BEC of two-state atoms

- Ideally, the BEC is in a single spatial mode.
- The state of an ensemble of the two-state atoms must be symmetric.
- In practice, the BEC is not in a single spatial mode, so there is no perfect symmetry.
- Our criterion must handle this.

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- Entanglement
- Collective measurements
- The original spin-squeezing criterion
- Generalized criteria for $j = \frac{1}{2}$, singlet states

3 Detecting multipartite entanglement of Dicke states

- Dicke state realized with a BEC of two-state atoms

4 Detecting bipartite entanglement of Dicke states

- Bipartite entanglement from multipartite entanglement in BEC
- Dicke state in a double well
- Problems to solve in an experiment
- Entanglement detection in Dicke states

Number-phase-like uncertainty

- We start from the sum of two Heisenberg uncertainty relations

$$(\Delta J_z)^2[(\Delta J_x)^2 + (\Delta J_y)^2] \geq \frac{1}{4}(\langle J_x \rangle^2 + \langle J_y \rangle^2).$$

Then,

$$(\Delta J_z)^2[(\Delta J_x)^2 + (\Delta J_y)^2] + \frac{1}{4}[(\Delta J_x)^2 + (\Delta J_y)^2] \geq \frac{1}{4}(\langle J_x^2 \rangle + \langle J_y^2 \rangle).$$

- Simple algebra yields

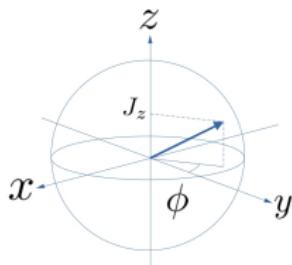
$$\left[(\Delta J_z)^2 + \frac{1}{4} \right] \times \frac{(\Delta J_x)^2 + (\Delta J_y)^2}{\langle J_x^2 \rangle + \langle J_y^2 \rangle} \geq \frac{1}{4}.$$

- Note that $\langle J_x^2 \rangle$ appears, not $\langle J_x \rangle^2$.

Number-phase-like uncertainty II

- Uncertainty relation

$$\underbrace{\left[(\Delta J_z)^2 + \frac{1}{4} \right]}_{\sim \text{fluctuation of } J_z} \times \underbrace{\frac{(\Delta J_x)^2 + (\Delta J_y)^2}{\langle J_x^2 \rangle + \langle J_y^2 \rangle}}_{\sim \text{phase fluctuation}} \geq \frac{1}{4}.$$



Handwaving description:

J_z and ϕ cannot be defined both with high accuracy.

Normalized variables

- Let us introduce the normalized variables

$$\mathcal{J}_m^n = \frac{J_m^n}{\sqrt{j_n(j_n + 1)}} \approx \frac{J_m^n}{N_n},$$

where $m = x, y$ and $n = a, b$ (i.e., left well, right well), the total spin is

$$j_n = \frac{N_n}{2},$$

- Normalized variables → resistance to experimental imperfections.

Uncertainty with normalized variables

Our uncertainty relation is now

$$\left[(\Delta J_z)^2 + \frac{1}{4} \right] \left[(\Delta \mathcal{J}_x)^2 + (\Delta \mathcal{J}_y)^2 \right] \geq \frac{1}{4} \langle \mathcal{J}_x^2 + \mathcal{J}_y^2 \rangle.$$

The two-well entanglement criterion

Suggestion of the experimentalists: we need a product criterion, since it is good for realistic noise.

Main result I

For separable states,

$$\left[(\Delta J_z)^2 + \frac{1}{4} \right] \left[(\Delta \mathcal{T}_x^-)^2 + (\Delta \mathcal{T}_y^-)^2 \right] \geq \frac{1}{16} \langle \mathcal{T}_x^2 + \mathcal{T}_y^2 \rangle^2$$

holds.

Here,

$$J_z = J_z^a + J_z^b,$$

$$\mathcal{T}_m^- = \mathcal{T}_m^a - \mathcal{T}_m^b$$

for $m = x, y$.

The two-well EPR-Steering criterion

Main result II

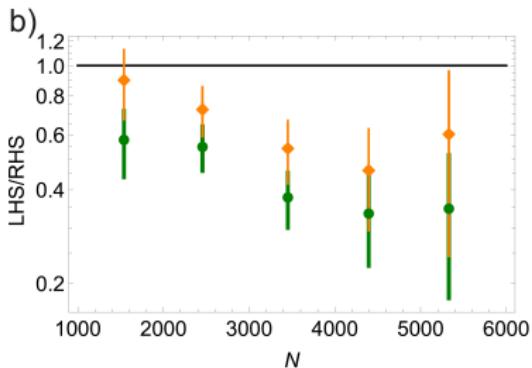
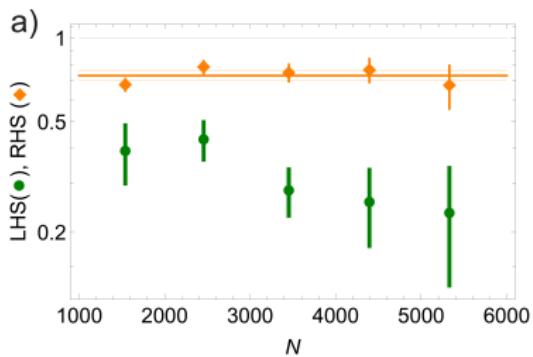
For states with a hidden state model,

$$\left[(\Delta J_z)^2 + \frac{1}{4} \right] \left[(\Delta \mathcal{J}_x^-)^2 + (\Delta \mathcal{J}_y^-)^2 \right] \geq \frac{1}{4} \langle (\mathcal{J}_x^a)^2 + (\mathcal{J}_y^a)^2 \rangle^2$$

holds.

Any state violating the inequality cannot be described by a hidden state model, i.e., the state is *steerable*.

Violation of the criterion: entanglement is detected II



(a) LHS/RHS for Quantum 2023, and (b) for Science 2018.

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Summary

- We discussed entanglement detection in particle ensembles.

THANK YOU FOR YOUR ATTENTION!

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