

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

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San Sebastian, October 4, 2024

Outline

1 Motivation

- Why entanglement is important?

2 Spin squeezing and entanglement

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

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
- Creating Dicke states in BEC
- Entanglement detection in Dicke states
- Our criteria work under realistic conditions

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.
- In many cases, we need to detect bipartite entanglement.

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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.

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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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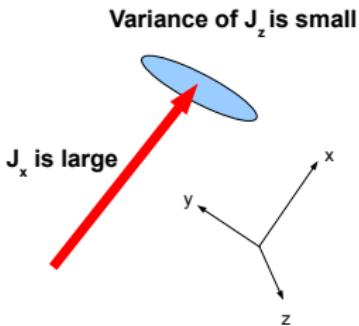
The standard spin-squeezing criterion

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!

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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 .

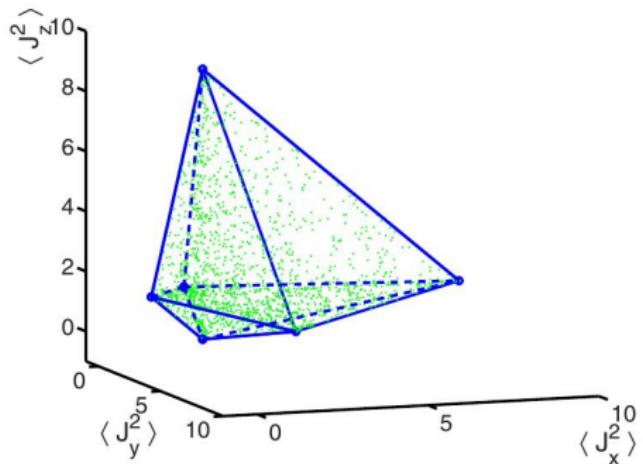
singlets: GT, Phys. Rev. A 69, 052327 (2004);

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 $l = x, y, z$.

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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.
- 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;

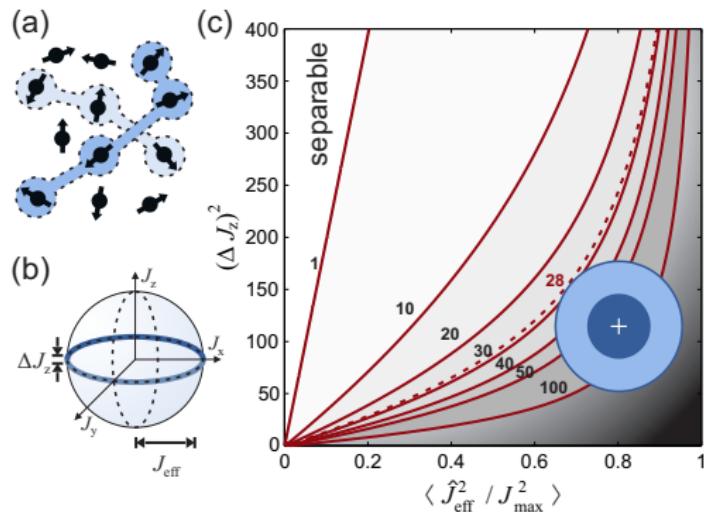
GT and Apellaniz, J. Phys. A, special issue for “50 year of Bell’s theorem”, 2014.

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

Fröwis, Dür, PRL 2011.

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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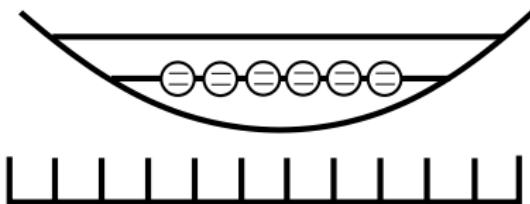
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Bipartite entanglement from bosonic multipartite entanglement

- 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!

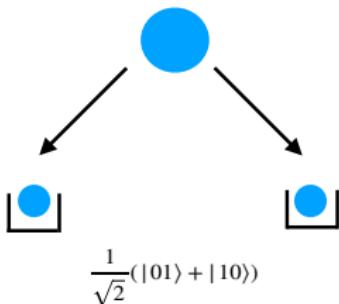
Bipartite entanglement from bosonic multipartite entanglement II

- Dilute cloud argument



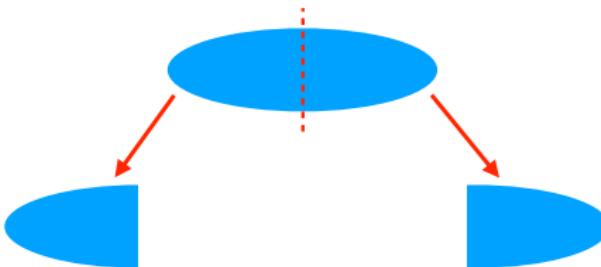
See, e.g., P. Hyllus, L. Pezzé, A Smerzi and GT, PRA 86, 012337 (2012)

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



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.

- Two-particle example:

$$|j_z = 0\rangle |j_z = 0\rangle \rightarrow \frac{1}{\sqrt{2}}(|j_z = +1\rangle |j_z = -1\rangle + |j_z = -1\rangle |j_z = +1\rangle)$$

= Dicke state of 2 particles.

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

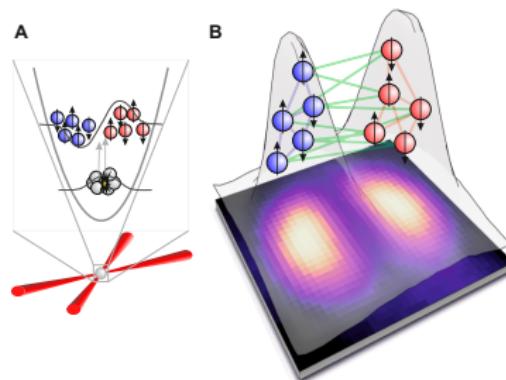
$$|D_N\rangle = \left(\frac{N}{\frac{N}{2}}\right)^{-\frac{1}{2}} \sum_k \mathcal{P}_k \left(|0\rangle^{\otimes \frac{N}{2}} \otimes |1\rangle^{\otimes \frac{N}{2}} \right),$$

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, G. Tóth, and C. Klempt, Entanglement between two spatially separated atomic modes, Science 360, 416 (2018).]

Correlations for Dicke states

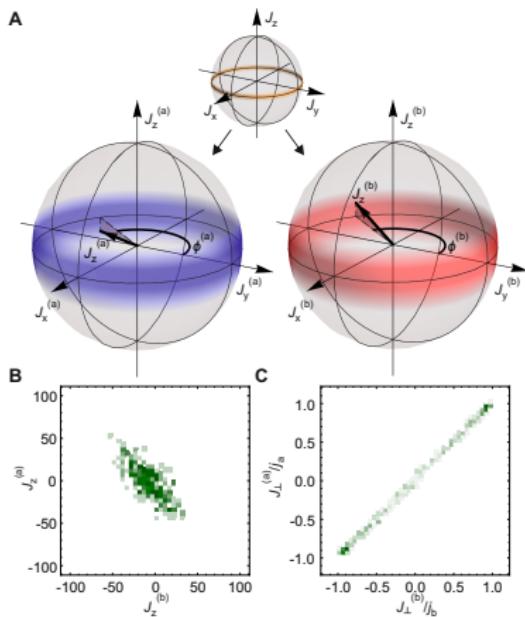
- For the Dicke state

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

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

$$\begin{aligned}J_x^b &\approx J_x^a, & \text{(correlation)} \\ J_y^b &\approx J_y^a, & \text{(correlation)} \\ J_z^b &= -J_z^a. & \text{(anti-correlation)}\end{aligned}$$

Correlations for Dicke states - experimental results



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

Experiment in K. Lange *et al.*, Science 334, 773–776 (2011).

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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

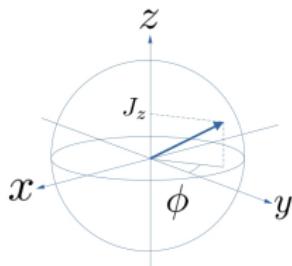
$$\left[(\Delta J_z)^2 + \frac{1}{4} \right] \times \frac{(\Delta J_x)^2 + (\Delta J_y)^2}{\langle J_x^2 \rangle + \langle J_y^2 \rangle} \geq \frac{1}{4}.$$

- 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

$$\mathcal{J}_x^n = \frac{J_x^n}{\sqrt{j_n(j_n + 1)}}, \quad \mathcal{J}_y^n = \frac{J_y^n}{\sqrt{j_n(j_n + 1)}},$$

where $n = a, b$ (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 EPR-Steering criterion

Main result I

For states with a hidden state model,

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

holds. $|D_N\rangle$: $1/4$ $\approx 4/N$ $\approx 1/4$

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

Here,

$$\begin{aligned} J_z &= J_z^a + J_z^b, \\ \mathcal{T}_x^- &= \mathcal{T}_x^a - \mathcal{T}_x^b, \\ \mathcal{T}_y^- &= \mathcal{T}_y^a - \mathcal{T}_y^b. \end{aligned}$$

The two-well entanglement criterion

Main result II

For separable states,

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

holds. $|D_N\rangle$: $1/4 \approx 4/N \approx 1$

Here,

$$\begin{aligned} J_z &= J_z^a + J_z^b, \\ \mathcal{J}_x^- &= \mathcal{J}_x^a - \mathcal{J}_x^b, \\ \mathcal{J}_y^- &= \mathcal{J}_y^a - \mathcal{J}_y^b. \end{aligned}$$

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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.
- Hence, the density matrix is of the form

$$\varrho = \sum_{N_a, N_b} Q_{N_a, N_b} \varrho_{N_a, N_b},$$

where Q_{N_a, N_b} are probabilities and ϱ_{N_a, N_b} are states.

- ϱ is entangled iff at least one of the ϱ_{N_a, N_b} is entangled.

Problem 1: Varying particle number II

- **Splitting noise:** 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

$$(\Delta N_a)^2 = (\Delta x)^2 = \langle x^2 \rangle = \frac{N}{4}, \quad (\Delta N_a) = \frac{\sqrt{N}}{2}$$

- Collective variance

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

Twice as large due to the unequal splitting.

Problem 1: Varying particle number III

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

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

- Real splitting with partition noise:

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

Problem 1: Varying particle number IV

- **Solution:** 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 $l = x, y$.

- We obtain

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

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

- We have

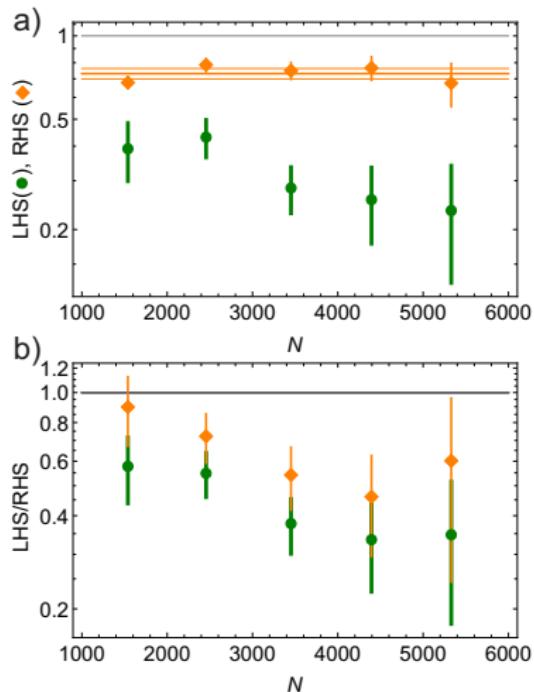
$$(\Delta \mathcal{J}_l^-)^2 \approx \frac{2}{N}.$$

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

Violation of the criterion: entanglement is detected II



LHS/RHS for (top) our present work, and (bottom) for Science 2018.

Collaborators on entanglement conditions for double-well Dicke states



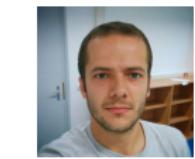
C. Klempf, I. Kruse, J. Peise,
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I. Apellaniz

Bilbao (G.T.)



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M. Kleinmann

ETH Zürich, Basel U. of Siegen

Summary

- Detection of bipartite entanglement and EPR steering close to Dicke states. It works also for split spin-squeezed states.
- Non-symmetric states within the wells and a varying particle number can also be handled.

G. Vitagliano, I. Apellaniz, M. Fadel, M. Kleinmann,
B. Lücke, C. Klempert, and G. Tóth,

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

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