New types of entangled states for metrology in space

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2nd Quantum Technology Workshop -
Implementations for Space
Amsterdam,
14 November 2017

Quantum entanglement

Quantum entanglement can improve the sensitivity of the cold gas interferometers

2.2.2. Advanced schemes The interest in applying atomic quantum gases to atom interferometry resides primarily in their coherence properties, which makes them more appealing than the thermal gases used so far in state-of-the-art interferometers. First, the naturally narrow momentum distribution of degenerate quantum gases represents an advantage with respect to a thermal gas produced in a standard MOT, where an additional selection stage is necessary to produce the required sub-recoil samples Second, the coherence of a quantum gas is the natural starting point to implement quantum techniques to improve the sensitivity of the interferometer, by the use of squeezing and/or entanglement, beyond the standard quantum limit. In this

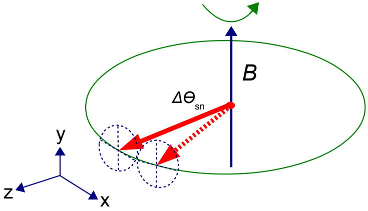
F. Sorrentino, K. Bongs, P. Bouyer et al., J. Phys.: Conf. Series 327, 012050 (2011).

Quantum metrology without entanglement

- For non-entangled states, the precision is bounded by the shot-noise limit as

$$(\Delta\theta)^2 \geq \frac{1}{N}.$$

- Estimating a rotation angle with a linear interferometer

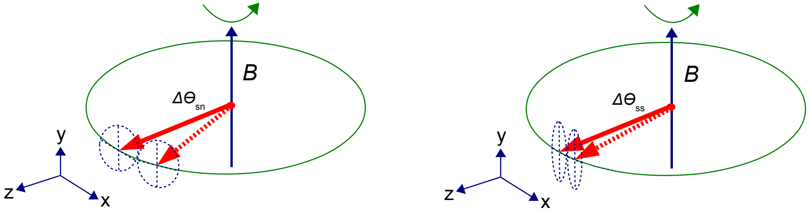


Quantum metrology with entanglement

- Possible to get a precision better than the shot-noise limit

$$(\Delta\theta)^2 \geq \frac{1}{N^2}.$$

- Entanglement (e.g., spin squeezing) is needed for a better precision



Quantum states going above the shot-noise limit

- Spin squeezed states.
  - Experiments in cold and hot atomic ensembles, BEC, with $10^3 - 10^{12}$ particles.
    [100 times spin squeezing: O. Hosten et al., Nature 2016.]
  - Cannot reach the best precision (realistic squeezing time). **-**
  - Robust to particle loss. **+**

- Greenberger-Horne-Zelinger (GHZ) states = Schrödinger cat states.
  - Experiments with up to 14 trapped ions.
  - In principle, can reach the best precision $(\Delta\theta)^2 = \frac{1}{N^2}$. **+**
  - Not robust. Single particle loss destroys all entanglement. **-**

Dicke states

- Symmetric Dicke states.
  - Half of the atoms in 0, half of them in 1, symmetric superposition.

$$\text{4-qubit Dicke state} = \frac{1}{\sqrt{6}}\left(|0011\rangle + |0101\rangle + ... + |1100\rangle\right).$$

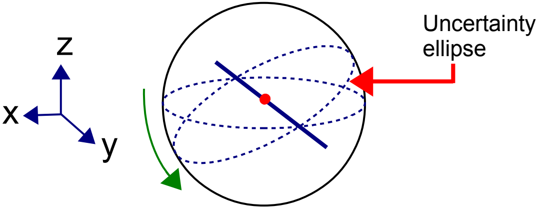
  - Experiments with thousands of atoms.
  - In principle, can reach the best possible precision $(\Delta\theta)^2 \sim \frac{1}{N^2}$. +
  - Robust to particle loss. +

Experiments with Dicke states

- Photonic experiments, groups of H. Weinfurter and A. Zelinger.
  - Six-photon Dicke state, creation, tomography, metrology.
- Cold gas experiments, group of C. Klempt, Hannover.
  - Demonstrating metrological usefulness
    Lücke et al., Science 2011
  - Detecting multipartite entanglement
    Lücke et al., PRL 2014
  - Detecting bipartite entanglement (split Dicke state)
    Lange et al., arxiv 2017

Metrology with Dicke states

Metrologically useful: 1.45 times shot-noise.



Rotating the uncertainty ellipse

Lücke, Scherer, Kruse, Pezzé, Deuretzbacher, Hyllus, Topic, Peise, Ertmer, Arlt, Santos, Smerzi, Klempt, Science 334, 773 (2011);
see also Apellaniz, Lücke, Peise, Klempt, GT, NJP 17, 083027 (2015).

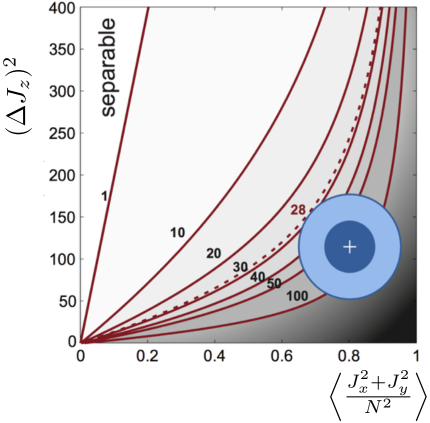
Experimental multipartite entanglement

Entanglement of more than 28 particles detected

$$N = 8000$$

$$\langle J_x^2 + J_y^2 \rangle \approx 0.8 N^2$$

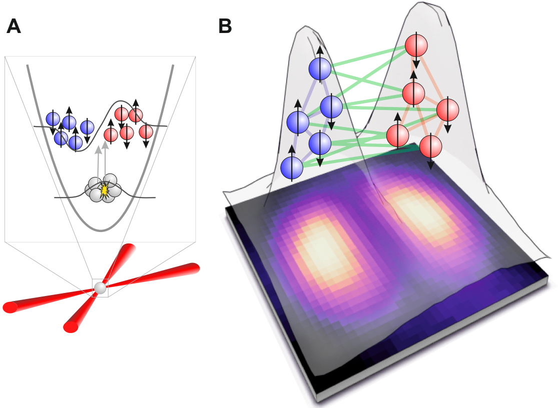
$$\langle J_z^2 \rangle \approx 100 \ll N$$



Lücke, Peise, Vitagliano, Arlt, Santos, GT, Klempt, PRL 112, 155304 (2014);
Vitagliano, Apellaniz, Kleinmann, Lücke, Klempt, GT, NJP 19, 013027 (2017).

Experimental bipartite entanglement

The Dicke state is split into two halves, entanglement is detected.



K. Lange, J. Peise, B. Lücke, I. Kruse, G. Vitagliano, I. Apellaniz, M. Kleinmann, GT, Klempt, arXiv:1708.02480 (2017).

Transparencies: www.gtoth.eu