

Quantum metrology

(Lecture of the Quantum Information class of the Master in Quantum Science and Technology)

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Outline

1 Motivation

- Why is quantum metrology interesting?

2 Simple examples of quantum metrology

- Classical case: Clock arm
- Quantum case: Single spin-1/2 particle
- Magnetometry with the fully polarized state
- Magnetometry with the spin-squeezed state
- Metrology with the GHZ state
- Dicke states
- Interferometry with squeezed photonic states

3 Entanglement theory

- Multipartite entanglement
- The spin-squeezing criterion

4 Quantum metrology using the quantum Fisher information

- Quantum Fisher information
- Quantum Fisher information in linear interferometers
- Noise and imperfections

Why is quantum metrology interesting?

- Recent technological development has made it possible to realize large coherent quantum systems, i.e., in cold gases, trapped cold ions or photons.
- Can such quantum systems outperform classical systems in something useful, i.e., metrology?

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3 Entanglement theory

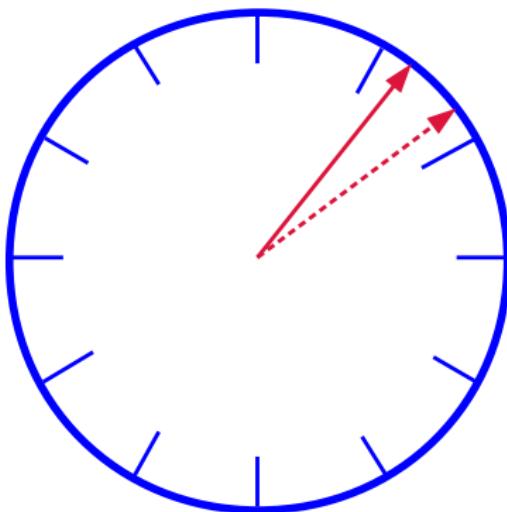
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Classical case: Estimating the angle of a clock arm

- Arbitrary precision ("in principle").



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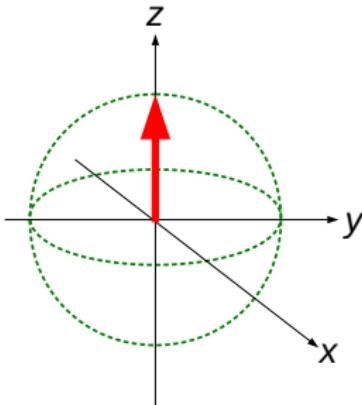
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Quantum case: A single spin-1/2 particle

- Spin-1/2 particle polarized in the z direction.



- We measure the spin components.

j_x

+1/2, 50%

-1/2, 50%

A diagram showing the measurement of the j_x component. It consists of two arrows originating from a central point. One arrow points upwards and to the left, labeled '+1/2, 50%'. The other arrow points downwards and to the left, labeled '-1/2, 50%'.

j_y

+1/2, 50%

-1/2, 50%

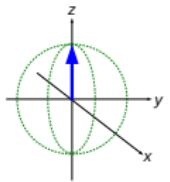
A diagram showing the measurement of the j_y component. It consists of two arrows originating from a central point. One arrow points upwards and to the right, labeled '+1/2, 50%'. The other arrow points downwards and to the right, labeled '-1/2, 50%'.

$j_z \rightarrow +1/2$

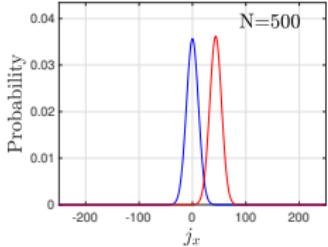
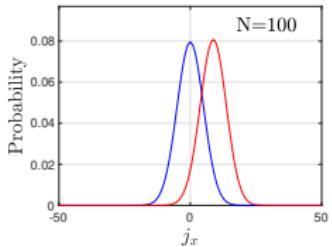
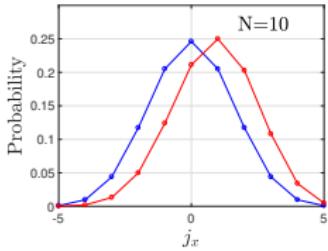
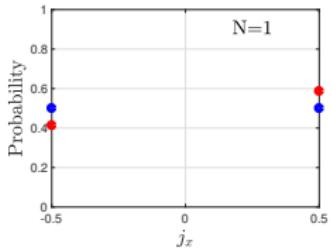
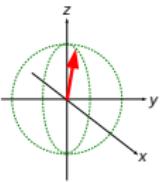
Quantum case: A single spin-1/2 particle II

- We cannot measure the three spin coordinates exactly j_x, j_y, j_z .
- In quantum physics, we can get only discrete outcomes in measurement. In this case, $+1/2$ and $-1/2$.
- A single spin-1/2 particle is not a good clock arm.

Several spin-1/2 particles



10° rotation
around y
⇒



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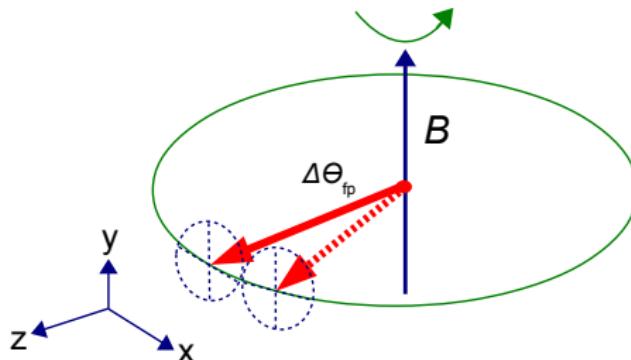
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Magnetometry with the fully polarized state

- N spin-1/2 particles, all fully polarized in the z direction.
- Magnetic field B points to the y direction.



- Note the uncertainty ellipses. $\Delta\theta_{fp}$ is the minimal angle difference we can measure.

Magnetometry with the fully polarized state II

- Collective angular momentum components

$$J_l := \sum_{n=1}^N j_l^{(n)}$$

for $l = x, y, z$, where $j_l^{(n)}$ are single particle operators.

- Dynamics

$$|\Psi\rangle = U_\theta |\Psi_0\rangle, \quad U_\theta = e^{-iJ_y\theta},$$

where $\hbar = 1$.

- Rotation around the y -axis.

Magnetometry with the fully polarized state III

- Let us assume, that we have an $M(\Theta)$ function.
- We know that there is an ΔM error in M .
- How much is the error $\Delta\theta$ in θ ?
- It is given by the classical **error propagation formula**:

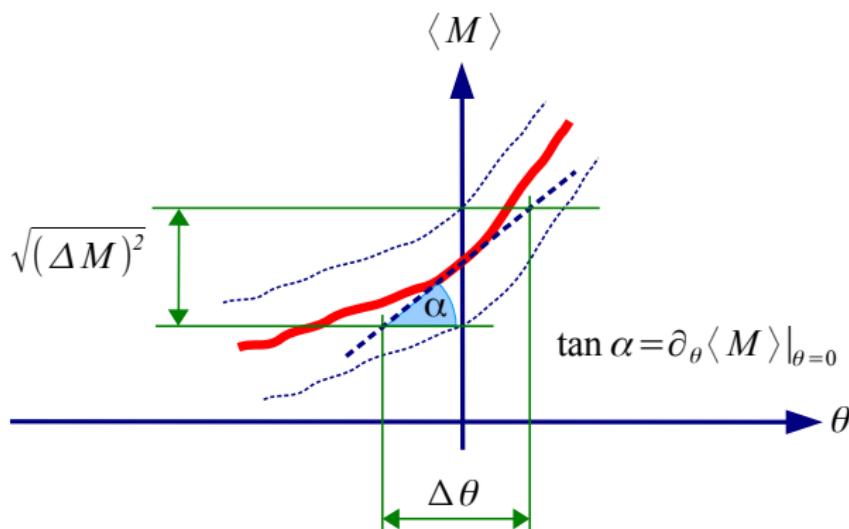
$$\Delta\theta \approx \frac{\Delta M}{dM/d\theta}.$$

- It tells us how the error in M "propagates" to θ .

Magnetometry with the fully polarized state IV

- Measure an operator M to get the estimate θ .
- To obtain the precision of estimation, we can use the **error propagation formula**

$$(\Delta\theta)_M^2 = \frac{(\Delta M)^2}{|\partial_\theta \langle M \rangle|^2} = \frac{(\Delta M)^2}{|\langle i[M, H] \rangle|^2}.$$



Magnetometry with the fully polarized state V

- In order to see the full picture, we need to consider ν measurements of M .
- We have to look for the average of the measured values

$$\bar{m} = \sum_{n=1}^{\nu} m_k.$$

- Then, if the measured probability distributions fulfill certain conditions, we can estimate the parameter with a precision

$$(\Delta\theta)^2 = \frac{1}{\nu} (\Delta\theta)_M^2 = \frac{1}{\nu} \frac{(\Delta M)^2}{|\partial_\theta \langle M \rangle|^2}.$$

[L. Pezze, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein,
"Quantum metrology with nonclassical states of atomic ensembles,"
Rev. Mod. Phys. 90, 035005 (2018).]

Magnetometry with the fully polarized state VI

- We consider the fully polarized states of N spin-1/2 particles

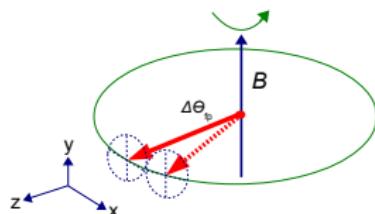
$$| +\frac{1}{2} \rangle^{\otimes N}.$$

- For this state,

$$\langle J_z \rangle = N/2, \quad \langle J_x \rangle = 0, \quad (\Delta J_x)^2 = N/4.$$

- We measure the operator

$$M = J_x.$$



- It is not like a classical clock arm, we have a nonzero uncertainty

$$(\Delta\theta)^2 = \frac{1}{\nu} \frac{(\Delta M)^2}{|\partial_\theta \langle M \rangle|^2} = \frac{1}{\nu} \frac{(\Delta J_x)^2}{\langle J_z \rangle^2} = \frac{1}{\nu} \frac{1}{N}.$$

Magnetometry with the fully polarized state VII

- Main result:

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

- In some cold gas experiment, we can have $10^3 - 10^{12}$ particles.
- Later we will see that with a separable quantum state we cannot have a better precision.

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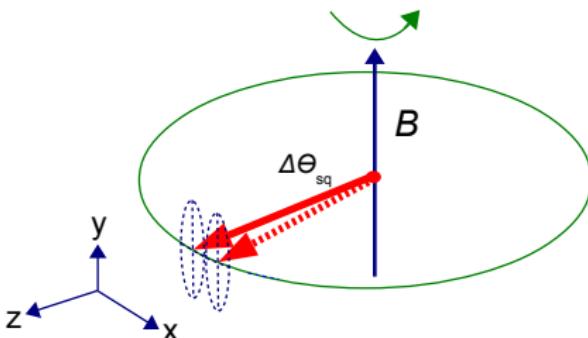
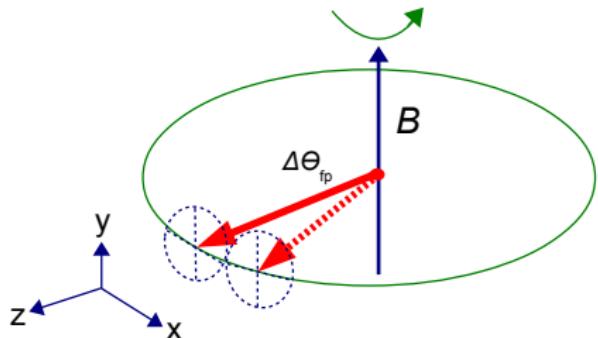
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Magnetometry with the spin-squeezed state

- We can increase the precision by spin squeezing



fully polarized state (fp)

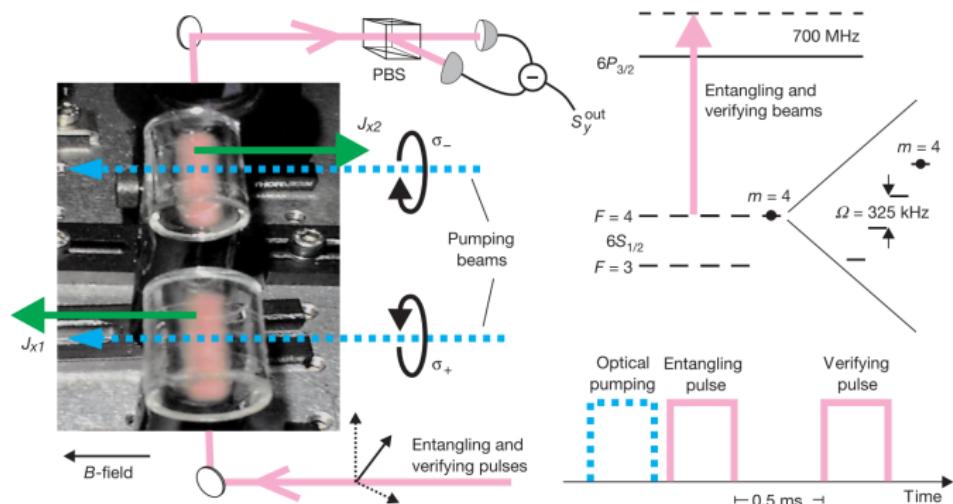
spin-squeezed state (sq)

$\Delta\theta_{fp}$ and $\Delta\theta_{sq}$ are the minimal angle difference we can measure.

We can reach

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

Spin squeezing in an ensemble of atoms via interaction with light

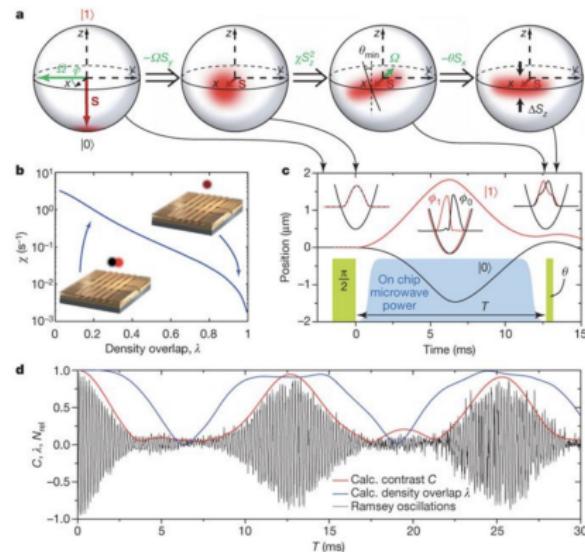


10^{12} atoms, room temperature.

Julsgaard, Kozhekin, Polzik, Nature 2001.

Spin squeezing in a Bose-Einstein Condensate via interaction between the particles

Figure 1: Spin squeezing and entanglement through controlled interactions on an atom chip.



M. F. Riedel, P. Böhi, Y. Li, T. W. Hänsch, A. Sinatra, and P. Treutlein,
Nature 464, 1170-1173 (2010).

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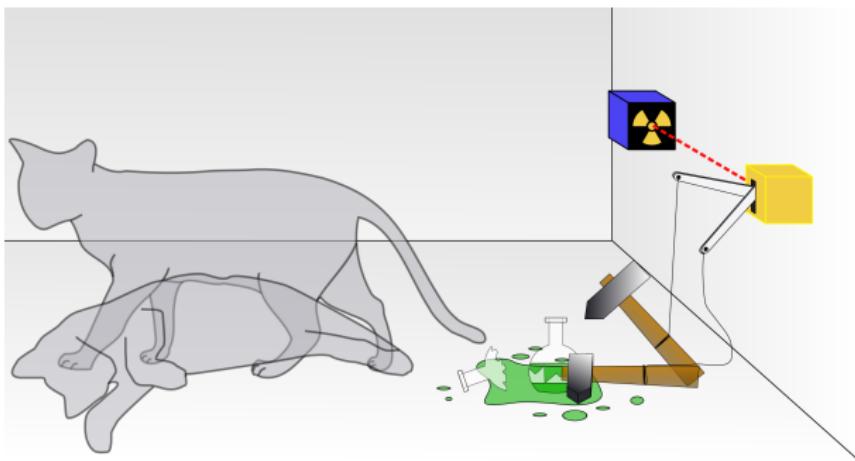
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GHZ state=Schrödinger cat state

- A superposition of two macroscopically distinct states



GHZ state

Greenberger-Horne-Zeilinger (GHZ) state

$$|GHZ_N\rangle = \frac{1}{\sqrt{2}}(|000\dots 00\rangle + |111\dots 11\rangle).$$

- Superposition of all atoms in state "0" and all atoms in state "1".

Metrology with the GHZ state

- Greenberger-Horne-Zeilinger (GHZ) state

$$|\text{GHZ}_N\rangle = \frac{1}{\sqrt{2}}(|000\dots 00\rangle + |111\dots 11\rangle),$$

- Unitary

$$|\Psi\rangle(\theta) = U_\theta |\text{GHZ}_N\rangle, \quad U_\theta = e^{-iJ_z\theta}.$$

- Dynamics

$$|\Psi\rangle(\theta) = \frac{1}{\sqrt{2}}(|000\dots 00\rangle + e^{-iN\theta}|111\dots 11\rangle),$$

Metrology with the GHZ state II

- We measure

$$M = \sigma_x^{\otimes N},$$

which is the parity in the x -basis.

- Expectation value and variance

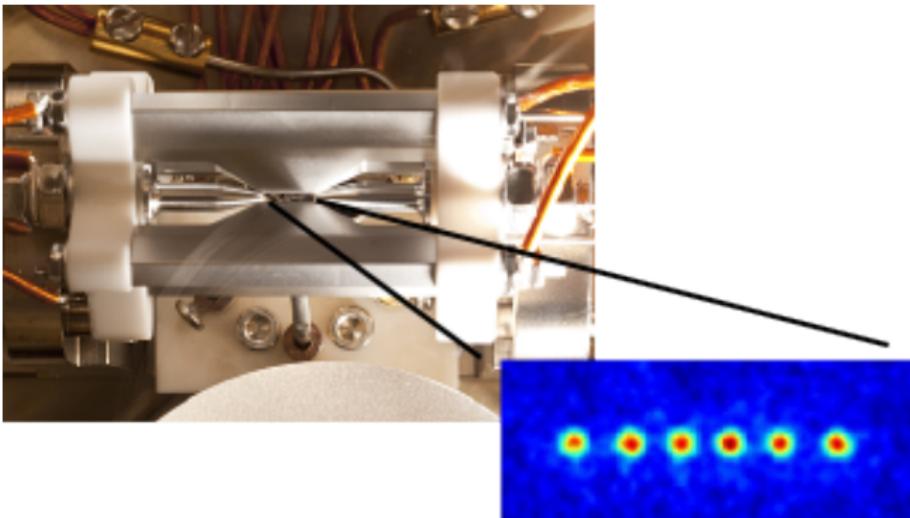
$$\langle M \rangle = \cos(\textcolor{red}{N}\theta), \quad (\Delta M)^2 = \sin^2(\textcolor{red}{N}\theta).$$

- For $\theta \approx 0$, the precision is

$$(\Delta\theta)^2 = \frac{1}{\nu} \frac{(\Delta M)^2}{|\partial_\theta \langle M \rangle|^2} = \frac{1}{\nu N^2}.$$

[e.g., photons: D. Bouwmeester, J. W. Pan, M. Daniell, H. Weinfurter and A. Zeilinger, Phys. Rev. Lett. 82, 1345 (1999);
ions: C. Sackett et al., Nature 404, 256 (2000).]

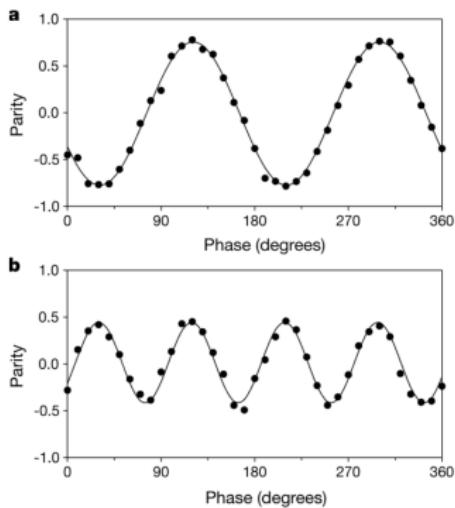
Metrology with the GHZ state III



Quantum Computation with Trapped Ions, Innsbruck

Metrology with the GHZ state IV

Figure 2: Determination of $p_{(\uparrow\downarrow)}$.



a, Interference signal for two ions; b, four ions. After the entanglement operation of Fig. 1, an analysis pulse with relative phase φ is applied on the single-ion $|\downarrow\rangle \leftrightarrow |\uparrow\rangle$ transition. As φ is varied, the parity of the N ions oscillates as $\cos N\varphi$, and the amplitude of the oscillation is twice the magnitude of the density-matrix element $p_{(\uparrow\downarrow)}$. Each data point represents an average of 1,000 experiments, corresponding to a total integration time of roughly 10 s for each graph.

For four ions the curve oscillates faster than for two ions.

[ions: C. Sackett et al., Nature 404, 256 (2000).]

Metrology with the GHZ state IV

- We reached the Heisenberg-limit

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

- The fully polarized state reached only the shot-noise limit

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

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Dicke states

- Symmetric Dicke states with $\langle J_z \rangle = 0$ (simply “Dicke states” in the following) are defined as

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

- 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: Kiesel, Schmid, GT, Solano, Weinfurter, PRL 2007;
Prevedel, Cronenberg, Tame, Paternostro, Walther, Kim, Zeilinger, PRL 2007;
Wieczorek, Krischek, Kiesel, Michelberger, GT, and Weinfurter, PRL 2009]

[cold atoms: Lücke *et al.*, Science 2011; Hamley *et al.*, Science 2011; C. Gross *et al.*, Nature 2011]

Metrology with Dicke states. Clock arm = noise

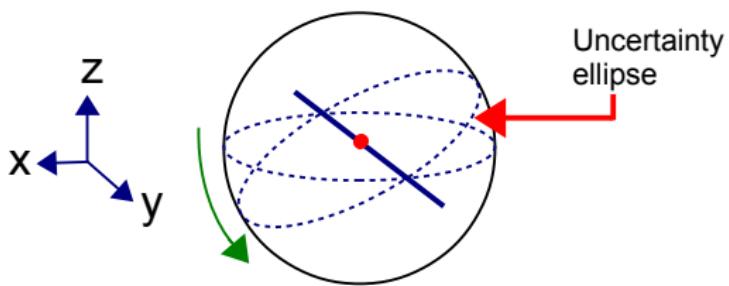
- For our symmetric Dicke state

$$\langle J_l \rangle = 0, l = x, y, z, \quad \langle J_z^2 \rangle = 0, \quad \langle J_x^2 \rangle = \langle J_y^2 \rangle = \text{large}.$$

- Linear metrology

$$U = \exp(-iJ_y\theta).$$

- Measure $\langle J_z^2 \rangle$ to estimate θ . (We cannot measure first moments, since they are zero.)



Metrology with Dicke states

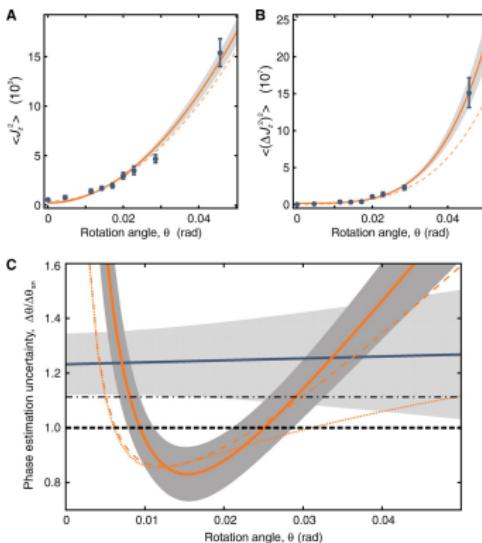
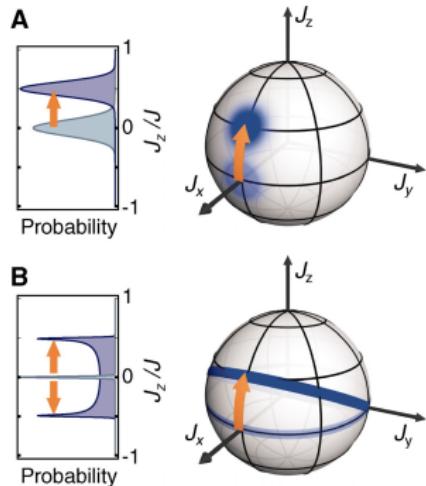
- Dicke states are more robust to noise than GHZ states. (Even if they loose a particle, they remain entangled).
- Dicke states can also reach the Heisenberg-scaling like GHZ states.

[Metrology with cold gases: B. Lücke, M Scherer, J. Kruse, L. Pezze, F. Deuretzbacher, P. Hyllus, O. Topic, J. Peise, W. Ertmer, J. Arlt, L. Santos, A. Smerzi, C. Klempt, Science 2011.]

[Metrology with photons: R. Krischek, C. Schwemmer, W. Wieczorek, H. Weinfurter, P. Hyllus, L. Pezze, A. Smerzi, PRL 2011.]

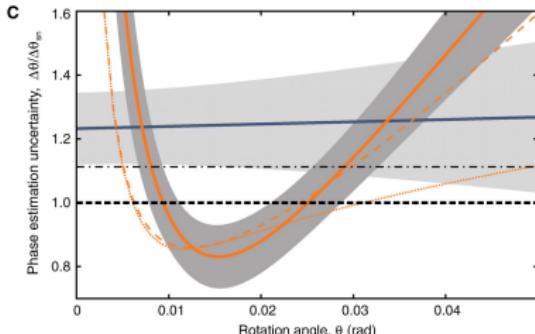
Metrology with Dicke states II

Experiment with cold gas of 8000 atoms.



[Lücke M. Scherer, Kruse, Pezzé, Deuretzbacher, Hyllus, Topic, Peise, Ertmer, Arlt, Santos, Smerzi, Klempt, Science 2011.]

Metrology with Dicke states III



- $\Delta\theta$ is the precision of estimating θ .
- $\Delta\theta_{\text{sn}}$ means the "shot-noise" uncertainty. This is the smallest uncertainty that could be achieved by separable states.
- Black dashed line = the level corresponding to $\Delta\theta/\Delta\theta_{\text{sn}} = 1$.
- Orange solid line = precision of estimating the angle θ in the experiment.
- The orange solid line is below the black dashed line around $\theta \approx 0.015$. Hence, the uncertainty $\Delta\theta$ is smaller than that could be achieved by any separable state, and hence the state of the system is entangled.

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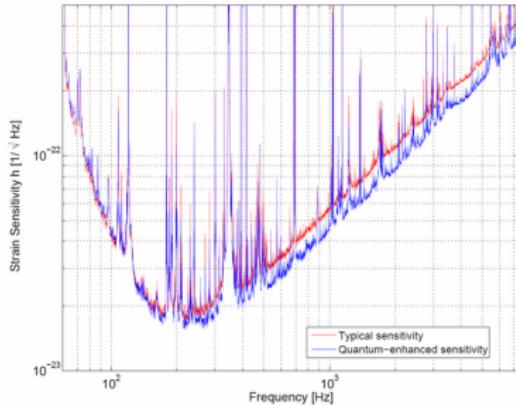
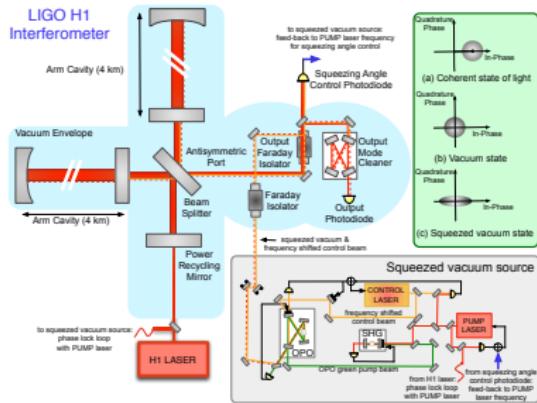
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LIGO gravitational wave detector

The performance was enhanced with squeezed light.



The role of clock arm is played by the squeezed coherent state.

[J. Aasi et al., Nature Photonics 2013.]

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Entanglement

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

$$\sum_k p_k \varrho_k^{(1)} \otimes \varrho_k^{(2)} \otimes \dots \otimes \varrho_k^{(N)}.$$

If a state is not separable then it is **entangled** (Werner, 1989).

k -producibility/ k -entanglement

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

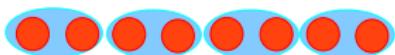
$$|\Phi\rangle = |\Phi_1\rangle \otimes |\Phi_2\rangle \otimes |\Phi_3\rangle \otimes |\Phi_4\rangle \dots$$

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., Ghne, GT, NJP 2005.]

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

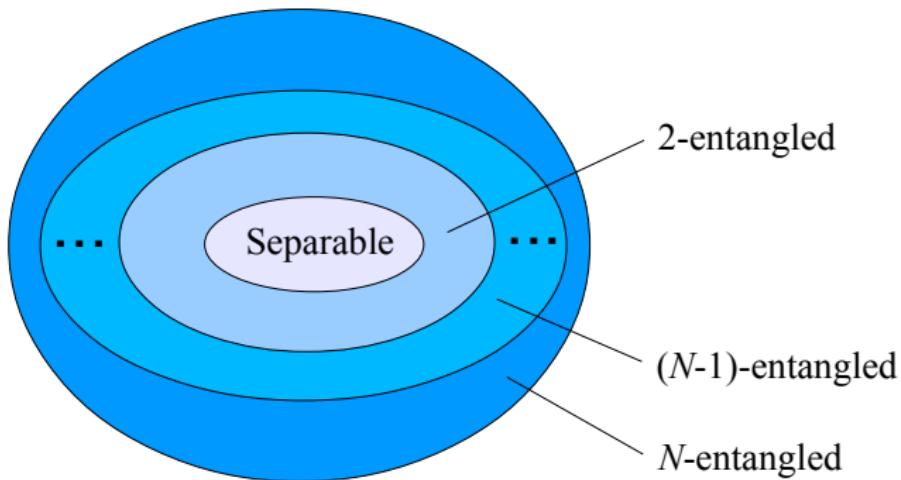


2-entangled



3-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

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The standard spin-squeezing criterion

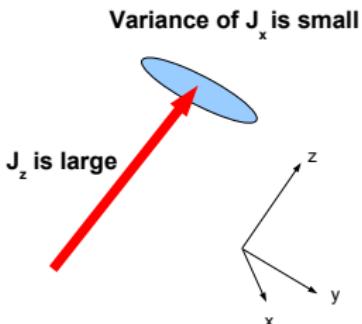
Spin squeezing criteria for entanglement detection

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

If $\xi_s^2 < 1$ then the state is entangled.

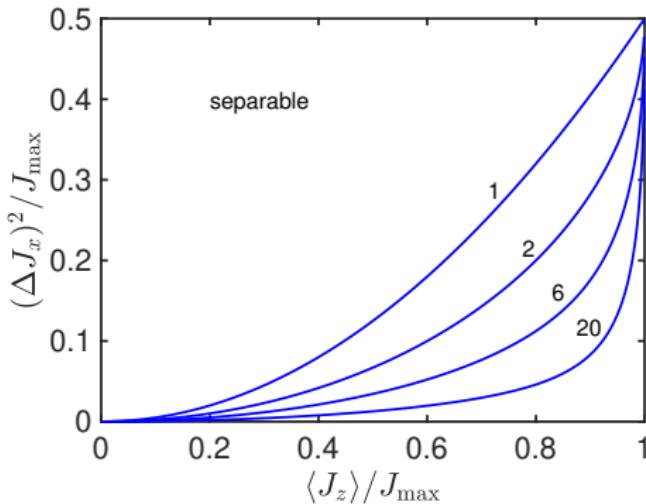
[Sørensen, Duan, Cirac, Zoller, Nature (2001).]

- States detected are like this:



Multipartite entanglement in spin squeezing

- 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).]

Our experience so far

- We find that more spin squeezing/better precision needs more entanglement.
- Question: Is this general?
- Answer: Yes.

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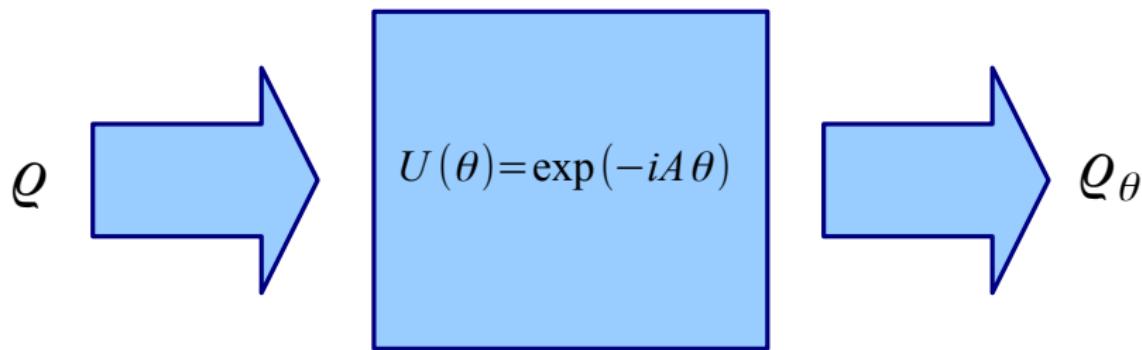
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Quantum metrology

- Fundamental task in metrology



- We have to estimate θ in the dynamics

$$U = \exp(-iA\theta).$$

The quantum Fisher information

Cramér-Rao bound on the precision of parameter estimation

For the variance of the parameter estimation

$$(\Delta\theta)^2 \geq \frac{1}{\nu F_Q[\varrho, A]}$$

holds, where ν is the number of repetitions and $F_Q[\varrho, A]$ is the **quantum Fisher information**.

- The bound includes any estimation strategy, even POVM's.
- The quantum Fisher information is

$$F_Q[\varrho, A] = 2 \sum_{k,l} \frac{(\lambda_k - \lambda_l)^2}{\lambda_k + \lambda_l} |\langle k | A | l \rangle|^2,$$

where $\varrho = \sum_k \lambda_k |k\rangle\langle k|$.

Convexity of the quantum Fisher information

- For pure states, it equals four times the variance,

$$F_Q[|\Psi\rangle, A] = 4(\Delta A)^2_{\Psi}.$$

- For mixed states, it is convex

$$F_Q[\varrho, A] \leq \sum_k p_k F_Q[|\Psi_k\rangle, A],$$

where

$$\varrho = \sum_k p_k |\Psi_k\rangle\langle\Psi_k|.$$

Quantum Fisher information - Some basic facts

- The larger the quantum Fisher information, the larger the achievable precision.
- For the totally mixed state it is zero for any A

$$F_Q[\varrho_{\text{cm}}, A] = 0,$$

where $\varrho_{\text{cm}} = \mathbb{1}/d$ is the completely mixed state and d is the dimension.

- This is logical: the completely mixed states does not change under any Hamiltonian.
- For any state ϱ that commutes with A , i.e., $\varrho A - A\varrho = 0$ we have

$$F_Q[\varrho, A] = 0.$$

Outline

1 Motivation

- Why is quantum metrology interesting?

2 Simple examples of quantum metrology

- Classical case: Clock arm
- Quantum case: Single spin-1/2 particle
- Magnetometry with the fully polarized state
- Magnetometry with the spin-squeezed state
- Metrology with the GHZ state
- Dicke states
- Interferometry with squeezed photonic states

3 Entanglement theory

- Multipartite entanglement
- The spin-squeezing criterion

4 Quantum metrology using the quantum Fisher information

- Quantum Fisher information
- Quantum Fisher information in linear interferometers
- Noise and imperfections

Magnetometry with a linear interferometer

- The Hamiltonian A is defined as

$$A = J_I = \sum_{n=1}^N j_I^{(n)}, \quad I \in \{x, y, z\}.$$

There are no interaction terms.

- The dynamics rotates all spins in the same way.

Quantum Fisher information for separable states

- Let us consider a pure product state of N qubits

$$|\Psi\rangle_{\text{prod}} = |\Psi^{(1)}\rangle \otimes |\Psi^{(2)}\rangle \otimes \dots \otimes |\Psi^{(N)}\rangle.$$

- Since this is a pure state, we have $F_Q[\varrho, J_I] = 4(\Delta J_I)^2|_{|\Psi\rangle_{\text{prod}}}.$
- Then, for the product state we have

$$(\Delta J_I)^2|_{|\Psi\rangle_{\text{prod}}} = \sum_{n=1}^N (\Delta j_I^{(n)})^2|_{|\Psi^{(n)}\rangle} \leq N \times \frac{1}{4},$$

where we used that for qubits $(\Delta j_I^{(n)})^2 \leq 1/4$.

- Since the quantum Fisher information is convex in the state, the bound is also valid for a mixture of product states, i.e., separable states

$$F_Q[\varrho, J_I] \leq N.$$

The quantum Fisher information vs. entanglement

- For separable states of N spin-1/2 particles (qubits)

$$F_Q[\varrho, J_l] \leq N, \quad l = x, y, z.$$

[Pezze, Smerzi, Phys. Rev. Lett. 102, 100401 (2009); Hyllus, Ghne, Smerzi, Phys. Rev. A 82, 012337 (2010)]

- For states with at most k -qubit entanglement (k is divisor of N)

$$F_Q[\varrho, J_l] \leq kN.$$

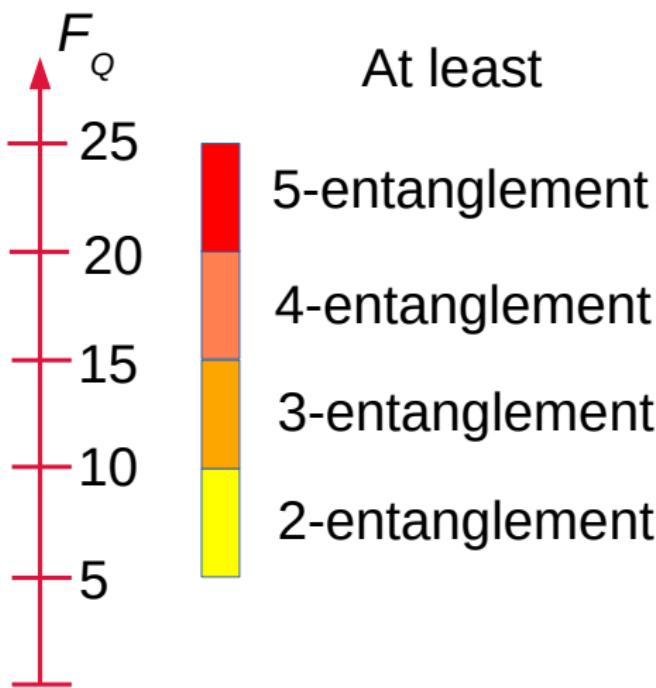
[P. Hyllus *et al.*, Phys. Rev. A 85, 022321 (2012); GT, Phys. Rev. A 85, 022322 (2012)].

- Bound for all quantum states of N qubits

$$F_Q[\varrho, J_l] \leq N^2.$$

The quantum Fisher information vs. entanglement

5 spin-1/2 particles



Let us use the Cramér-Rao bound

- For separable states

$$(\Delta\theta)^2 \geq \frac{1}{\nu N}, \quad l = x, y, z.$$

[Pezze, Smerzi, Phys. Rev. Lett. 102, 100401 (2009); Hyllus, Gühne, Smerzi, Phys. Rev. A 82, 012337 (2010)]

- For states with at most k -particle entanglement (k is divisor of N)

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

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- Bound for all quantum states

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

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Noisy metrology: Simple example

- A particle with a state ϱ_1 passes through a map that turns its internal state to the fully mixed state with some probability p as

$$\epsilon_p(\varrho_1) = (1 - p)\varrho_1 + p\frac{1}{2}.$$

- This map acts in parallel on all the N particles.
- Metrology with a spin squeezed state

$$(\Delta\theta)^2 = \frac{1}{\nu} \frac{(\Delta J_x)^2}{\langle J_z \rangle^2} \geq \frac{1}{\nu} \frac{\frac{pN}{4}}{\frac{N^2}{4}} = p \frac{1}{\nu N} \propto \frac{1}{\nu N}.$$

- Shot-noise scaling if $p > 0$.

[G. Toth, and I. Apellaniz, J. Phys. A: Math. Theor. 47, 424006 (2014).]

Noisy metrology: General treatment

- In the most general case, uncorrelated single particle noise leads to shot-noise scaling after some particle number.

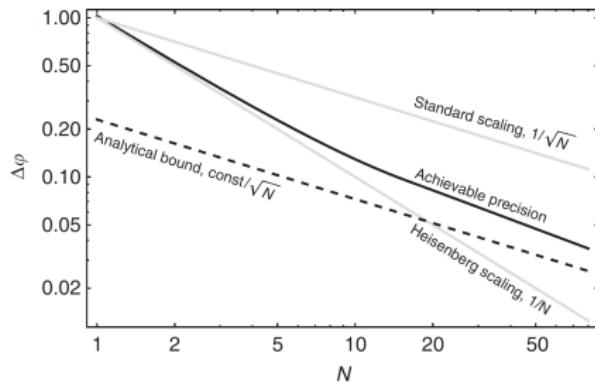


Figure from

[R. Demkowicz-Dobrzański, J. Kołodyński, M. Guća, Nature Comm. 2012.]

- Correlated noise is different.

Take home message

- Quantum physics makes it possible to obtain bounds for precision of the parameter estimation in realistic many-particle quantum systems.
- Shot-noise limit: Non-entangled states lead to $(\Delta\theta)^2 \geq \frac{1}{\nu N}$.
- Heisenberg limit: Fully entangled states can lead to $(\Delta\theta)^2 = \frac{1}{\nu N^2}$.
- At the end, noise plays a central role.

Reviews

- M. G. A. Paris, Quantum estimation for quantum technology, *Int. J. Quantum Inf.* 7, 125 (2009).
- V. Giovannetti, S. Lloyd, and L. Maccone, Advances in quantum metrology, *Nat. Photonics* 5, 222 (2011).
- C. Gross, Spin squeezing, entanglement and quantum metrology with Bose-Einstein condensates, *J. Phys. B: At., Mol. Opt. Phys.* 45, 103001 (2012).
- R. Demkowicz-Dobrzanski, M. Jarzyna, and J. Kolodynski, Chapter four-quantum limits in optical interferometry, *Prog. Opt.* 60, 345 (2015).
- L. Pezze, A. Smerzi, M. K. Oberthaler, R. Schmied, and P. Treutlein, Non-classical states of atomic ensembles: fundamentals and applications in quantum metrology, *Rev. Mod. Phys.* 90, 035005 (2018).

Summary

- We reviewed quantum metrology from a quantum information point of view.

See:

Géza Tóth and Iagoba Apellaniz,

Quantum metrology from a quantum information science perspective,

J. Phys. A: Math. Theor. 47, 424006 (2014),
special issue "50 years of Bell's theorem"
(open access).