Quantum metrology

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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.
- Can such quantum systems outperform classical systems in something useful, i.e., metrology?

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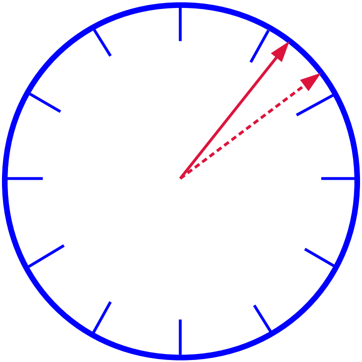
Classical case: Estimating the angle of a clock arm

- Arbitrary precision ("in principle").



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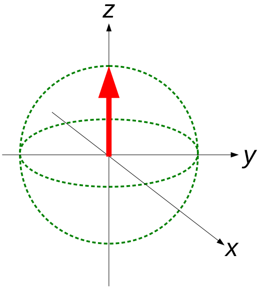
Quantum case: A single spin-$1/2$ particle

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



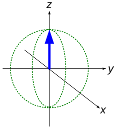
- We measure the spin components.

$$j_x \begin{array}{l} \nearrow \; +1/2, \;\; 50\% \\ \\ \searrow \; -1/2, \;\; 50\% \end{array} \qquad j_y \begin{array}{l} \nearrow \; +1/2, \;\; 50\% \\ \\ \searrow \; -1/2, \;\; 50\% \end{array} \qquad j_z \rightarrow +1/2$$

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

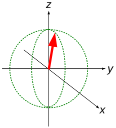
- We cannot measure the three spin coordinates exactly j_x, j_y, j_z.
- In quantum physics, we can get only discrete outcomes in measurement. In this case, $+1/2$ and $-1/2$.
- A single spin-1/2 particle is not a good clock arm.

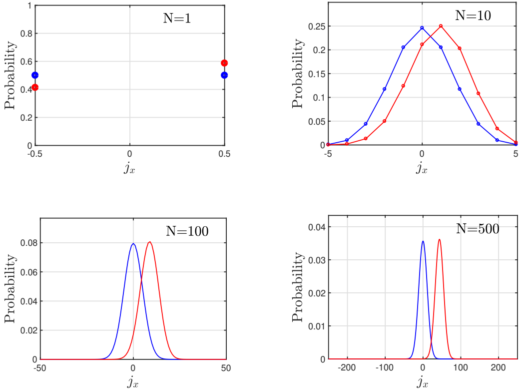
Several spin-1/2 particles



10^{o} rotation around y

$\Rightarrow$





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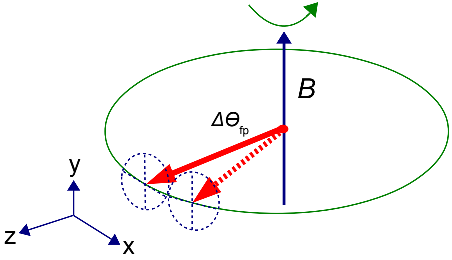
Magnetometry with the fully polarized state

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



- Note the uncertainty ellipses. $\Delta\theta_{\rm fp}$ 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

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

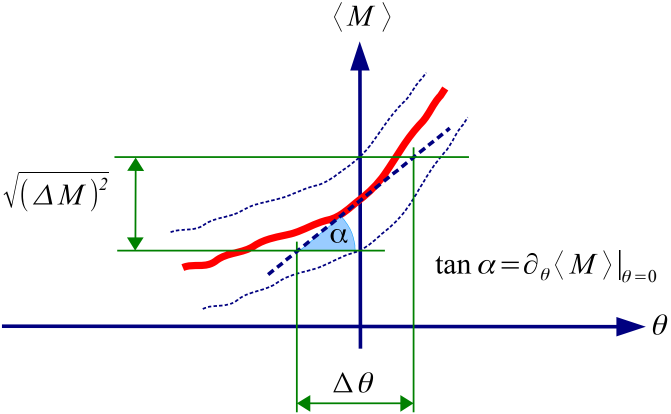
  where $\hbar = 1$.

- Rotation around the y-axis.

Magnetometry with the fully polarized state III

- Measure an operator M to get the estimate θ.
- The precision is given by the error propagation formula

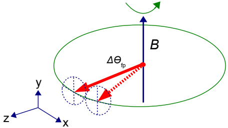
$$(\Delta\theta)^2 = \frac{(\Delta M)^2}{|\partial_\theta \langle M \rangle|^2}.$$



Magnetometry with the fully polarized state IV

- We measure the operator

$$M = J_x.$$



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

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

Magnetometry with the fully polarized state VI

- Main result:

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

- In some cold gas experiment, we can have $10^3 - 10^{12}$ particles.

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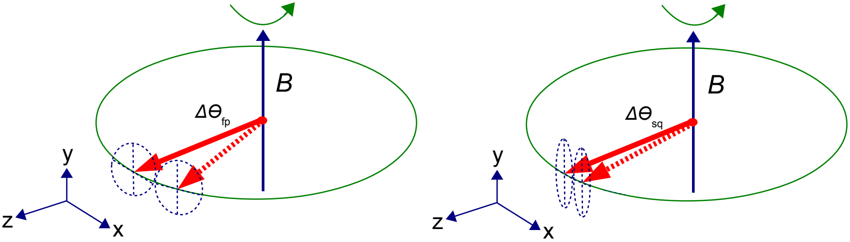
Magnetometry with the spin-squeezed state

- We can increase the precision by spin squeezing



fully polarized state (fp)

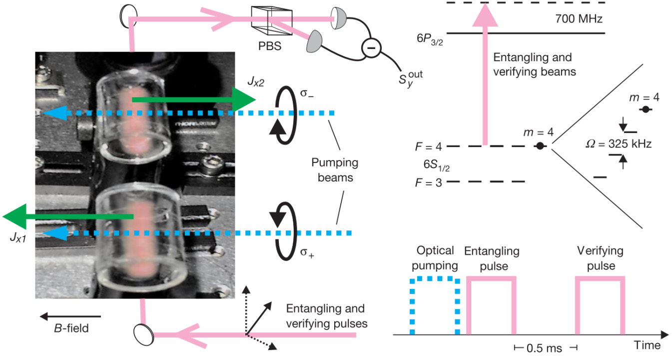
spin-squeezed state (sq)

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

We can reach

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

Spin squeezing in an ensemble of atoms via interaction with light

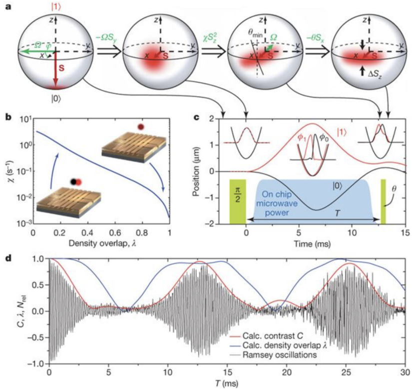


10^{12} atoms, room temperature.

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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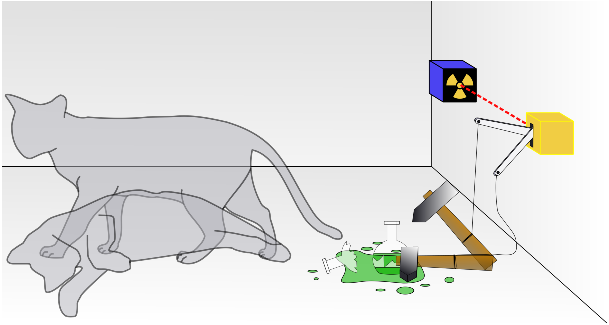
GHZ state=Schrödinger cat state

- A superposition of two macroscopically distinct states



GHZ state

Greenberger-Horne-Zeilinger (GHZ) state

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

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

Metrology with the GHZ state

- Greenberger-Horne-Zeilinger (GHZ) state

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

- Unitary

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

- Dynamics

$$|\Psi\rangle(\theta) = \tfrac{1}{\sqrt{2}}(|000...00\rangle + e^{-i{\color{red}N}\theta}|111...11\rangle),$$

Metrology with the GHZ state II

- We measure
$$M = \sigma_x^{\otimes N},$$
which is the parity in the x-basis.

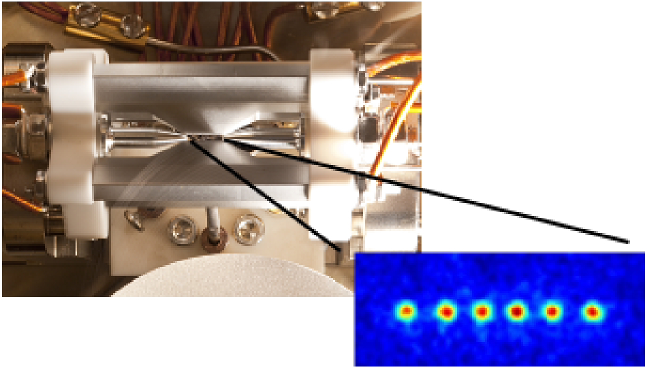
- Expectation value and variance
$$\langle M \rangle = \cos(N\theta), \qquad (\Delta M)^2 = \sin^2(N\theta).$$

- For $\theta \approx 0$, the precision is
$$(\Delta\theta)^2 = \frac{(\Delta M)^2}{|\partial_\theta \langle M \rangle|^2} = \frac{1}{N^2}.$$

[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).]

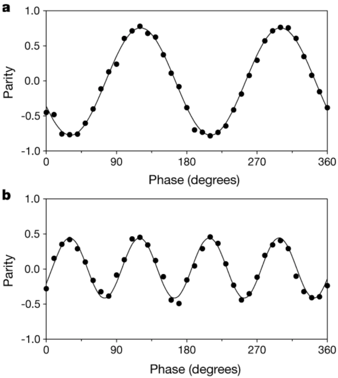
Metrology with the GHZ state III



Quantum Computation with Trapped Ions, Innsbruck

Metrology with the GHZ state IV

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



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*φ, and the amplitude of the oscillation is twice the magnitude of the density-matrix element $\rho_{(\uparrow\downarrow)}$. Each data point represents an average of 1,000 experiments, corresponding to a total integration time of roughly 10 s for each graph.

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

Metrology with the GHZ state IV

- We reached the Heisenberg-limit

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

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

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

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Dicke states

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

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

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

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

[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

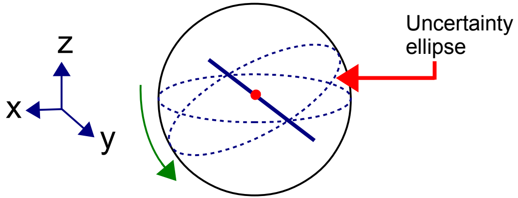
- For our symmetric Dicke state

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

- 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

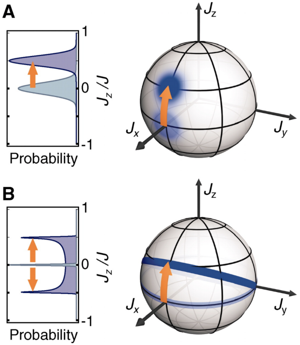
- Dicke states are more robust to noise than GHZ states.
- Dicke states can also reach the Heisenberg-scaling like GHZ states.

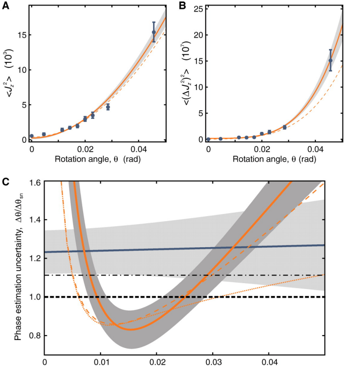
[Metrology with cold gases: B. Lücke, M Scherer, J. Kruse, L. Pezze, F. Deuretzbacher, P. Hyllus, O. Topic, J. Peise, W. Ertmer, J. Arlt, L. Santos, A. Smerzi, C. Klempt, Science 2011.]

[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.]

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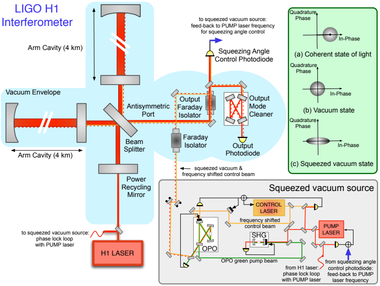
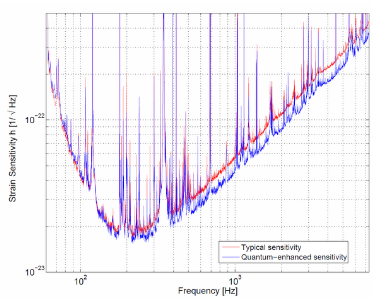
LIGO gravitational wave detector

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

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

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

k-producibility/k-entanglement

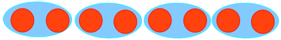
A pure state is *k*-producible if it can be written as

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

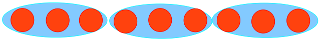
where $|\Phi_l\rangle$ are states of at most k qubits.

A mixed state is k-producible, if it is a mixture of k-producible pure states.
[e.g., Gühne, GT, NJP 2005.]

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

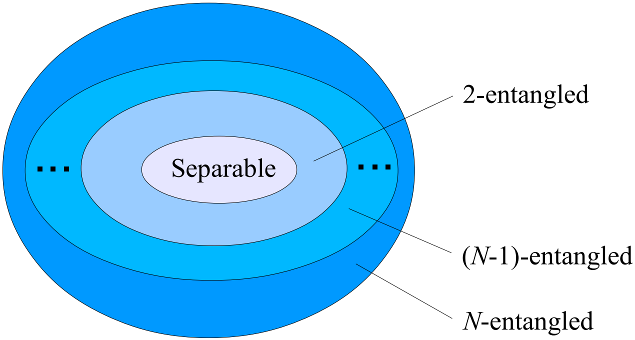


2-entangled



3-entangled

k-producibility/k-entanglement II



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

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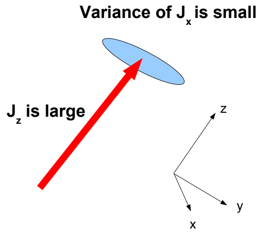
The standard spin-squeezing criterion

Spin squeezing criteria for entanglement detection

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

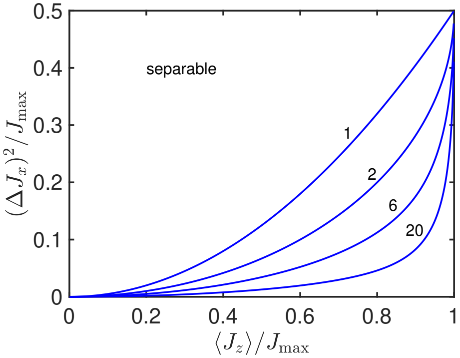
If $\xi_s^2 < 1$ then the state is entangled.
[Sørensen, Duan, Cirac, Zoller, Nature (2001).]

- 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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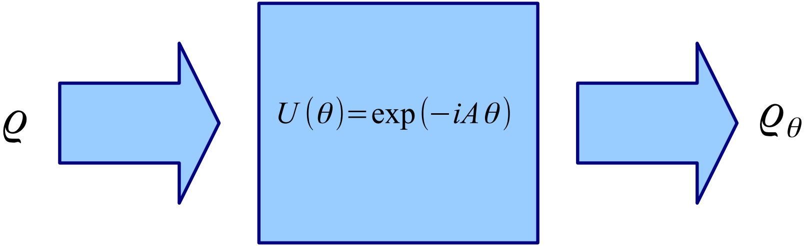
Quantum metrology

- Fundamental task in metrology



- We have to estimate θ in the dynamics

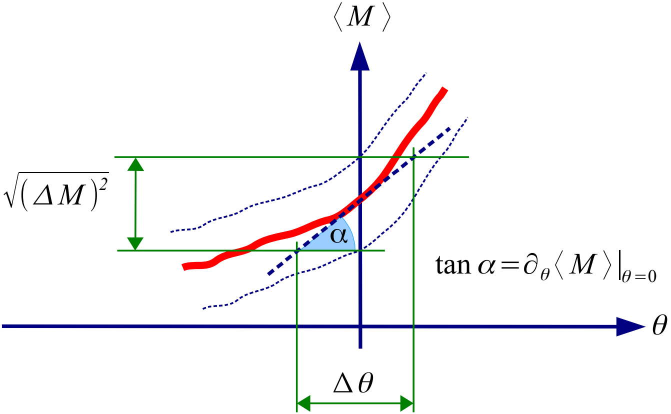
$$U = \exp(-iA\theta).$$

Precision of parameter estimation (slide repeated)

- Measure an operator M to get the estimate θ.

- The precision is given by the error propagation formula

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



The quantum Fisher information

Cramér-Rao bound on the precision of parameter estimation

For every M

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

where $F_Q[\varrho, A]$ is the quantum Fisher information.

- The bound is even more general, 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

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

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

$$A = J_l = \sum_{n=1}^{N} j_l^{(n)}, \quad l \in \{x, y, z\}.$$

  There are no interaction terms.

- The dynamics rotates all spins in the same way.

The quantum Fisher information vs. entanglement

- For separable states

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

[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)

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

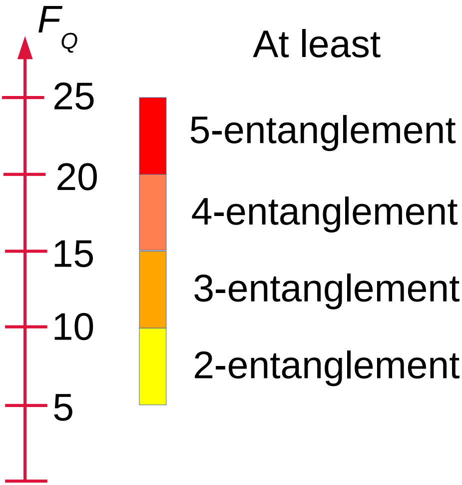
[P. Hyllus *et al.*, Phys. Rev. A 85, 022321 (2012); GT, Phys. Rev. A 85, 022322 (2012)].

- Bound for all quantum states

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

The quantum Fisher information vs. entanglement

5 spin-1/2 particles



Let us use the Cramér-Rao bound

- For separable states

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

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

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Noisy metrology: Simple example

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

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

- This map acts in parallel on all the N particles.

- Metrology with spin squeezed state

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

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

Noisy metrology: General treatment

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

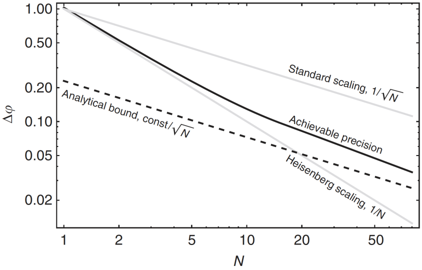

Figure from
[R. Demkowicz-Dobrzański, J. Kołodyński, M. Guţă, Nature Comm. 2012.]

- 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 $(\Delta\theta)^2 \geq \frac{1}{N}$.
- Heisenberg limit: Fully entangled states can lead to $(\Delta\theta)^2 = \frac{1}{N^2}$.
- At the end, noise plays a central role.

Reviews

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- 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, arXiv:1609.01609.

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).

Please see the slides at www.gtoth.eu.