Quantum metrology with Dicke squeezed states

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Abstract

We introduce a new class of quantum many-particle entangled states, called the Dicke squeezed (or DS) states, which can be used to improve the precision in quantum metrology beyond the standard quantum limit. We show that the enhancement in measurement precision is characterized by a single experimentally detectable parameter, called the Dicke squeezing $\xi_D$, which also bounds the entanglement depth for this class of states. The measurement precision approaches the ultimate Heisenberg limit as $\xi_D$ attains the minimum in an ideal Dicke state. Compared with other entangled states, we show that the DS states are more robust to decoherence and give better measurement precision under typical experimental noise.

Keywords: quantum metrology, Dicke squeezed state, entanglement

Precision measurement plays an important role for scientific and technological applications. In many circumstances, precision measurement can be reduced to detection of a small phase shift by use of optical or atomic interferometry [1–4]. The precision of the phase measurement improves with increase of the number of particles (photons or atoms) in the interferometer. For $N$ particles in non-entangled (classical) states, the phase sensitivity $\Delta \theta$ is constrained by the standard quantum limit $\Delta \theta \sim 1/\sqrt{N}$ from the shot noise [1, 3, 4]. Schemes have been proposed to improve the measurement precision beyond the standard quantum limit by use of quantum entangled states [1–7]. Two classes of states are particularly important for this scenario: one is the GHZ state [6], also called the NOON state in the second quantization representation [7]; and
the other is the spin squeezed state [1, 3, 4], which may include the squeezed state of light as a special limit. A number of intriguing experiments have been reported to prepare these states and use them for quantum metrology [8–14]. These states are typically sensitive to decoherence and experimental noise [15, 16]. As a result, the number of particles that one can prepare into the GHZ state, or the maximal spin squeezing that one can achieve, are both severely limited by noise in experiment.

In this paper, we introduce a new class of many-particle entangled states for quantum metrology, which we name the Dicke squeezed (DS) states. The DS states have the following interesting features: (i) They represent a wide class of entangled states with possibly many different forms but can be characterized by a single parameter called the Dicke squeezing \( \xi_D \), with \( \xi_D < 1 \). The Dicke squeezing parameter \( \xi_D \) can be conveniently measured in experiments from detection of the collective spin operator of \( N \) particles. It provides the figure-of-merit for application of the DS states in quantum metrology in the following sense: for states with \( \xi_D \), the phase sensitivity \( \Delta \theta \) and the phase measurement precision \( d\theta \) both improve from the standard quantum limit \( 1/\sqrt{N} \) to the new scaling \( \sqrt{\xi_D}/N \). The phase shift can be read out through the Bayesian inference for the DS states. Under a fixed particle number \( N \), the parameter \( \xi_D \) attains the minimum \( 1/(N + 2) \) under the ideal Dicke state, and the phase sensitivity correspondingly approaches the Heisenberg limit \( \Delta \theta \sim 1/N \), in agreement with the previous result on the Dicke state [17, 18]. (ii) The entanglement of the DS states can be also characterized by the squeezing parameter \( \xi_D \). For a many-body system with a large particle number \( N \), we would like to know how many particles among them have been prepared into genuinely entangled states. This number of particles with genuine entanglement is called the entanglement depth for this system [19, 20]. A criterion proved in [20] indicates that \( \xi_D^{-1} - 2 \) gives a lower bound of the entanglement depth for any DS states with the squeezing parameter \( \xi_D \). (iii) Compared with the GHZ state or the spin squeezed states, we show that the DS states characterized by \( \xi_D \) are much more robust to decoherence and experimental noise such as particle loss. Substantial Dicke squeezing \( \xi_D \) remains under a significant amount of noise under which spin squeezing would not be able to survive at all.

For a system of \( N \) particles, each of two internal states \( a, b \) (with effective spin-1/2), we can define a Pauli matrix \( \sigma_i \) for each particle \( i \) and the collective spin operator \( \vec{J} \) as the summation \( \vec{J} = \sum_i \vec{\sigma}_i / 2 \). Note that the components of \( \vec{J} \) can be measured globally without the requirement of separate addressing of individual particles. If the particles are indistinguishable like photons or ultracold bosonic atoms, we can use the number of particles \( n_a, n_b \) in each mode \( a, b \) to denote the states. In this notation (second quantization representation), the GHZ state of \( N \) spins \( |aaa\ldots a\rangle + |bbb\ldots b\rangle \) (unnormalized) is represented by \( |N0\rangle_{ab} + |0N\rangle_{ab} \), the so called NOON state [7]. The collective spin operators can be expressed in term of the mode operators \( a, b \) using the Schwinger representation \( J_z = (a^\dagger a - b^\dagger b)/2 \), \( J_y = (a^\dagger b - b^\dagger a)/2i \) [2]. Asmall phase shift \( \theta \) can be measured through the Mach–Zehnder (MZ) type of interferometer illustrated in figure 1 by inputting a state of two modes \( a, b \) and measuring the number difference of the output modes (the output \( J_z \) operator). The two beam splitters in the interferometer exchange the \( J_z \) and \( J_y \) operators and the phase shifter is represented by a unitary operator \( e^{i\delta J_z} \), which transforms \( J_y \) to \( \cos \theta J_y - \sin \theta J_z \). Assume the input state has mean \( \langle \vec{J} \rangle = \langle J_z \rangle \) and minimum variance \( \langle \Delta J_y^2 \rangle \) along the \( y \)-direction. By measuring \( \langle J_y' \rangle = \cos \theta \langle J_y \rangle - \sin \theta \langle J_z \rangle \approx -\theta \langle J_z \rangle \), the phase sensitivity \( \Delta \theta \) is characterized by \( \sqrt{\langle \Delta J_y^2 \rangle / \langle J_z \rangle} \). This motivates definition of the spin squeezing parameter [3, 4]
ξ1 = Δ

\( \xi_{S} = \frac{N \left\langle (\Delta J_{z})^2 \right\rangle}{\left\langle J_{z} \right\rangle^2} \) (1)

as the figure-of-merit for precision measurement. The phase sensitivity is estimated by \( \sqrt{\xi_{S}/N} \) for this measurement scheme.

Not all states useful for quantum metrology can be characterized by the spin squeezing \( \xi_{S} \). An example is the Dicke state \( |N/2, N/2\rangle_{ab} \), which has been shown to give the Heisenberg limited phase sensitivity in [17]. However, for this state, \( \left\langle \vec{J} \right\rangle = 0 \) in all the directions, and the spin squeezing \( \xi_{S} \) is not a good measure to characterize states of this kind with \( \left\langle \vec{J} \right\rangle = 0 \). To characterize a broad class of states that are useful for quantum metrology, we introduce the following Dicke squeezing parameter, defined as

\( \xi_{D} = \frac{N \left\langle (\Delta J_{z})^2 \right\rangle + \frac{1}{4}}{\left\langle J_{z}^2 + J_{x}^2 \right\rangle} \) (2)

One can easily check that \( \xi_{D} = 1 \) for the benchmark spin-coherent states. We call any states with \( \xi_{D} < 1 \) as the DS states and a major result of this paper is to show that such states are useful for quantum metrology, where the phase sensitivity is improved from \( \sqrt{1/N} \) for the benchmark spin coherent state to about \( \sqrt{\xi_{D}/N} \) for the DS states. The parameter \( \xi_{D} \) attains the minimum \( 1/(N + 2) \) under the ideal Dicke state \( |N/2, N/2\rangle_{ab} \), and the phase sensitivity \( \sqrt{\xi_{D}/N} \) correspondingly approaches the Heisenberg limit \( \sim 1/N \), in agreement with the results in [17, 18]. The definition of the parameter \( \xi_{D} \) is motivated by a similar quantity first introduced in the work [20] for detection of many-particle entanglement. Another related parameter is \( \xi_{os} = (N - 1)\left\langle (\Delta J_{z})^2 \right\rangle / \left\{ \left\langle J_{z}^2 + J_{x}^2 \right\rangle - N/2 \right\} \), introduced in [21] for entanglement detection. Albeit similar in form, for metrological applications \( \xi_{os} \) makes more sense as it recovers the correct Heisenberg limit \( (\xi_{D} \to 1/N, \text{ in contrast with } \xi_{os} \to 0) \) as one approaches the Dicke states.

The Dicke squeezing parameter \( \xi_{D} \) also characterizes the entanglement depth \( E_d \) for many-particle systems. For an \( \hat{N} \)-qubit system, the entanglement depth \( E_d \) measures how many qubits...
have been prepared into genuinely entangled states [19, 20]. A theorem proven in Ref. shows that \[
\xi_D^{-1} \ll 2, \]
where \[
\xi_D^{-1}
\] denotes the minimum integer no less than \[
\xi_D^{-1}
\] gives a lower bound of the entanglement depth \(E_d\). For the ideal Dicke state, \(|N/2, N/2\rangle_{ab}\), \(\xi_D^{-1} = N + 2\) and its entanglement depth is \(N\) [20]. Note that the entanglement depth characterizes the particle (qubit) entanglement when we express the state \(|N/2, N/2\rangle_{ab}\) in the first quantization representation [19, 20], where one can easily see all the \(N\) qubits are genuinely entangled, so its entanglement depth is \(N\). This should not be confused with the mode entanglement between the bosonic operators \(a\) and \(b\), which is zero for the Dicke state \(|N/2, N/2\rangle_{ab}\). So the defined Dicke squeezing parameter \(\xi_D\) provides a figure-of-merit both for entanglement characterization and its application in quantum metrology, and this parameter can be conveniently measured in experiments through detection of the collective spin operator \(J\).

To show that \(\xi_D\) is the figure-of-merit for quantum metrology, we use two complementary methods to verify that the phase measurement precision is improved to \(\sqrt{\xi_D}/N\) for a variety of states of different forms. First, in the MZ interferometer shown in figure 1(a), the phase sensitivity is estimated by the intrinsic uncertainty \(\Delta \theta\) of the relative phase operator defined between the two arms (modes \(a_\pm\)). We calculate this phase uncertainty and find that it scales as \(\sqrt{\xi_D}/N\) for various input states with widely different \(\xi_D\) and \(N\). Second, we directly estimate the phase shift \(\theta\) by the Bayesian inference through detection of the spin operator \(J_z\), and find that the measurement precision, quantified by the variance \(d\theta\) of the posterior phase distribution, is well estimated by \(\beta \sqrt{\xi_D}/N\), where \(\beta \approx 1.7\) is a dimensionless prefactor. We perform numerical simulation of experiments with randomly chosen phase shift \(\theta\) and find that the difference between the actual \(\theta\) and the measured value of \(\theta\) obtained through the Bayesian inference is well bounded by the variance \(d\theta\), so \(d\theta\) is indeed a good measure of the measurement precision.

The Dicke state \(|N/2, N/2\rangle_{ab}\) represents an ideal limit, and it is hard to obtain a perfect Dicke state in experiments in particular when the particle number \(N\) is large. Here, we consider two classes of more practical states as examples to show that \(\xi_D\) is the figure-of-merit for application in quantum metrology when the ideal Dicke state is distorted by unavoidable experimental imperfection. For the first class, we consider pure states of the form \(|\Psi(\sigma)\rangle_{ab} = \sum_{n=0}^{N} a_n(\sigma)|n, N - n\rangle\), where the total number of particles is fixed to be \(N\) but the number difference between the modes \(a, b\) follows a Gaussian distribution \(a_n(\sigma) = \exp \left\{ -\frac{N^2}{\sigma^2} + i \frac{\pi}{4} (n - N) \right\}\) with different widths characterized by the parameter \(\sigma\). The phase of \(a_n(\sigma)\) is chosen for convenience so that the variance of the state is symmetric along the \(x, y\) axes. For the second class, we consider mixed states \(\rho_{ab}(\eta)\), which come from noise distortion of the Dicke state \(|N/2, N/2\rangle_{ab}\) after a particle loss channel with varying loss rate \(\eta\). To calculate \(\rho_{ab}(\eta)\), we note that a loss channel with loss rate \(\eta\) can be conveniently modeled by the transformation \(a = \sqrt{1 - \eta} a_m + \sqrt{\eta} a_v\) and \(b = \sqrt{1 - \eta} b_m + \sqrt{\eta} b_v\), where \(a_m, b_m\) denote the annihilation operators of the input modes that are in the ideal Dicke state \(|N/2, N/2\rangle = ((N/2)\rangle^{-1}(a_m^\dag b_m)^N|0, 0\rangle\) and \(a_v, b_v\) represent the corresponding vacuum modes. By substituting \(a_m^\dag, b_m^\dag\) with \(a^\dag, b^\dag\) through the channel transformation and tracing over the vacuum modes \(a_v^\dag b_v^\dag\), we get the matrix form of \(\rho_{ab}(\eta)\) in the Fock basis of the modes \(a, b\). The two classes of states \(|\Psi(\sigma)\rangle_{ab}\) and \(\rho_{ab}(\eta)\) approach the ideal Dicke state when the parameters \(\sigma, \eta\) tend to zero.

In the MZ interferometer shown in figure 1(a), the modes \(a_\pm\) of the two arms are connected with the input modes \(a, b\) by the relation \(a_\pm = (\pm a + b)/\sqrt{2}\). The phase eigenstates \(|\theta\rangle_{\pm}\) of the modes \(a_\pm\) are superpositions of the corresponding Fock states \(|n\rangle_{\pm}\) with
where \( \delta l = \theta_l (s + 1)/(2\pi) \). The phase distribution \( P(\theta_r) \) becomes independent of the Hilbert space dimension \( s + 1 \) when \( s \) goes to infinity, and the half width \( \Delta \theta \) of \( P(\theta_r) \) gives an indicator of the intrinsic interferometer sensitivity to measure the relative phase shift for the given input state \([17, 18]\). We use \( \Delta \theta \) to quantify the phase sensitivity for our input states.

In figure 2, we show the calculated phase sensitivity \( \Delta \theta \) for the two classes of input states \( |\Psi(\sigma)\rangle_{ab} \) and \( \rho_{\sigma\eta}(\eta) \), by varying the parameters \( \sigma, \eta \) and the particle number \( N \). With fixed parameters \( \sigma, \eta \), when we vary the particle number \( N \) (typically from 20 to 200 in our calculation), the phase sensitivity \( \Delta \theta \) follows a linear dependence with the parameter \( \sqrt{\xi_D/N} \) by \( \Delta \theta = \alpha \sqrt{\xi_D/N} \) (note that the Dicke squeezing parameter \( \xi_D \) changes widely as we vary \( N \) and \( \sigma, \eta \)). The slope \( \alpha \) depends very weakly on the parameters \( \sigma, \eta \), as shown in figure 2(c) and (d), and roughly we have \( \alpha \approx 2 \). This shows that, for different types of input states, the phase sensitivity \( \Delta \theta \) is always determined by the parameter \( \sqrt{\xi_D/N} \) up to an almost constant prefactor \( \alpha \).
A good phase sensitivity $\Delta \theta$ is an indicator of possibility of high-precision measurement of the relative phase shift $\theta$, however, the sensitivity by itself does not give the information of $\theta$. In particular, for the DS states, we typically have $\langle J \rangle = 0$ and therefore cannot read out the information of $\theta$ by measuring rotation of the mean value of $J$. A powerful way to read out the information of $\theta$ is through the Bayesian inference [17, 18]. Here, we show that with the Bayesian inference, we can faithfully extract the information of $\theta$ with a measurement precision $d\theta = \beta \sqrt{\Delta J/N}$ for the DS states, where the prefactor $\beta \approx 1.7$. We note that each instance of measurement by the MZ interferometer setup shown in figure 1 records one particular eigenvalue $j_i$ of the $J_z$ operator, which occurs with a probability distribution $P(j_i|\theta)$ (called the likelihood) that depends on the relative phase shift $\theta$. With a given input state $\rho_{ab}$ for the modes $a, b$, the likelihood $P(j_i|\theta)$ is given by

$$P(j_i|\theta) = \langle j_i | e^{i\theta J_z} | j_i \rangle,$$

where $|j_i, j_i\rangle$ denotes the momentum eigenstate with $j = N/2$. The Bayesian inference is a way to use the Bayes’ rule to infer the posterior distribution $P_m(\theta | \{j_i\}_m)$ of the phase shift $\theta$ after $m$ instances of measurements of the $J_z$ operator with the measurement outcomes $\{j_i\}_m = j_{i_1}, j_{i_2}, \cdots, j_{i_m}$, respectively. After the $m$th measurement with outcome $j_{i_m}$, the phase distribution $P_m(\theta | \{j_i\}_m)$ is updated by the Bayes’ rule

$$P_m(\theta | \{j_i\}_m) = \frac{P(j_{i_m} | \theta) P_{m-1}(\theta | \{j_i\}_{m-1})}{P(j_{i_m} | \{j_i\}_{m-1})},$$

where $P(j_{i_m} | \{j_i\}_{m-1}) = \int d\theta P(j_{i_m} | \theta) P_{m-1}(\theta | \{j_i\}_{m-1})$ is the probability to get the outcome $j_{i_m}$ conditional on the sequence $\{j_i\}_{m-1}$ for the previous $m - 1$ measurement outcomes. Before the first measurement, the prior distribution $P_0(\theta)$ is assumed to be a uniform distribution between 0 and $2\pi$. When the instances of measurements $m \gg 1$, the posterior distribution $P_m(\theta | \{j_i\}_m)$ is typically sharply peaked around the actual phase shift, and we use the half width $d\theta$ of $P_m(\theta | \{j_i\}_m)$ to quantify the measurement precision.

To show that the measurement precision $d\theta$ is indeed determined by $\sqrt{\Delta J/N}$ for the DS states, we numerically simulate the MZ experiment with a randomly chosen actual phase shift $\theta$, in the interferometer. We take input states of the forms of $|\{}{}\rangle_p$, respectively. After the first measurement, the prior distribution $P_0(\theta)$ is assumed to be a uniform distribution between 0 and $2\pi$. When the instances of measurements $m \gg 1$, the posterior distribution $P_m(\theta | \{j_i\}_m)$ is typically sharply peaked around the actual phase shift, and we use the half width $d\theta$ of $P_m(\theta | \{j_i\}_m)$ to quantify the measurement precision.

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experiments (the scattered points) is typically below the corresponding $\theta_d$. This supports our central claim: the defined Dicke squeezing parameter $\xi_D$ characterizes the improvement of measurement precision for the DS states compared with the standard quantum limit.

Compared with other entangled states used in quantum metrology, a remarkable advantage of the DS states characterized by the squeezing parameter $\xi_D$ is its noise robustness. For instance, if the noise in experiments is dominated by the dephasing error that does not change the mode population, the numerator does not change in the definition equation (2) for the Dicke squeezing $\xi_D$ and only the denominator drops slowly. With a dephasing rate $p$ ($p$ is the probability for each qubit to become completely decoherent), the squeezing parameter reduces to $\xi_D = 1/[N (1 - p) + 2 - p^2]$ if we start with a Dicke state for $N$ particles [20]. We still have substantial squeezing when $N \gg 1$ even if the dephasing error rate $p \gtrsim 50\%$. More generic noise such as particle loss has a larger influence on the Dicke squeezing, however, the DS states are still more robust compared with other forms of entangled states such as the spin squeezed states. In figure 4(a), we show the influence of the particle loss to the Dicke squeezing $\xi_D$ and the spin squeezing $\xi_S$, starting with comparable values of $\xi_S$ and $\xi_D$ at the loss rate $\eta = 0$ under the same particle number $N$. The spin squeezed state was determined by minimizing $\Delta J_z$ with $J_z = 0.1J$ [19]. One can see that the spin squeezing $\xi_S$ is quickly blown up by very small particle loss, but substantial Dicke squeezing $\xi_D$ remains even under a significant loss rate. In

![Figure 3](image-url)
the asymptotic limit with $N \gg 1$, $\xi_D \approx \eta/(1 - \eta)$ under a loss rate $\eta$. Therefore, compared with the standard quantum limit, the measurement precision improves by a constant factor of $\sqrt{\xi_D} \approx \sqrt{\eta/(1 - \eta)}$ for the DS state under loss. This has saturated the bound derived in [23], which proves that under noise the measurement process can be improved at most by a constant factor for any quantum entangled states (the factor is exactly $\sqrt{\eta/(1 - \eta)}$ under a loss rate $\eta$ as proven in [23]). The saturation of the improvement bound shows that the DS states characterized by the parameter $\xi_D$ belong to the optimal class of states for improving the measurement precision under noise (note that the conventional spin squeezed states measured by the squeezing parameter $\xi_S$ are not optimal for improving measurement precision under noise as $\xi_S$ is quickly blown up to be larger than 1 (see figure 4 (a)), yielding no improvement compared with the standard quantum limit). Another source of noise important for experiments is the fluctuation in the total particle number $N$. The squeezing $\xi_D$ is robust to this fluctuation. To show this, we consider $\xi_D$ under an initial states, which is an ensemble of Dicke states with various particle numbers $N$ mixed together according to the Poissonian distribution $P_N = \lambda^N e^{-\lambda}$ with $\langle N \rangle = \lambda$. In figure 4(b), we compare $\xi_D$ under this state and $\xi_D^{id}$ under a single Dicke state with a fixed particle number $N = \lambda$. One can see that the difference is small, indicating that the Dicke squeezing $\xi_D$ is insensitive to the total number fluctuation in the initial state.

In summary, we have proposed a new class of many-particle entangled states characterized by the introduced Dicke squeezing parameter $\xi_D$ to improve the measurement precision in quantum metrology. We show that the phase information can be read out through the Bayesian inference and the measurement precision is improved by a factor of $\sqrt{\xi_D}$ compared with the
standard quantum limit. A distinctive advantage of the DS states is its noise robustness and we show that the Dicke squeezing \( \xi_D \) is much more robust compared with other forms of entangled states used in quantum metrology. Substantial Dicke squeezing can be generated in experiments, for instance, through the atomic collision interaction in spinor condensates [24, 25]. With the characterization and measurement method proposed in this paper, the Dicke squeezing may lead to a fruitful approach for precision quantum metrology using entangled quantum states.

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