NONLINEAR INTERFEROMETRY

Measure in circles

Entanglement can provide an extra boost in precision, but entangled states are hard to detect. A recent experiment solves this problem by letting the entangling dynamics come full circle — or not, depending on the subtle perturbation to be sensed.

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The sensitivity of devices such as atomic clocks, magnetometers and gravimeters is limited by statistical fluctuations inherent in the probabilistic nature of quantum measurements. The fluctuations can be reduced by first allowing the constituent atoms to interact and thereby acquire quantum correlations. Typically, longer interaction times lead to stronger entanglement and thus, in principle, to higher sensitivity. This makes entanglement a critical resource for advancing precision measurements, but the most highly entangled states are often the most difficult to detect. Now, writing in *Nature Physics*, Qi Liu and colleagues report that they have solved this problem through a clever design of interactions that give rise to a cyclic time

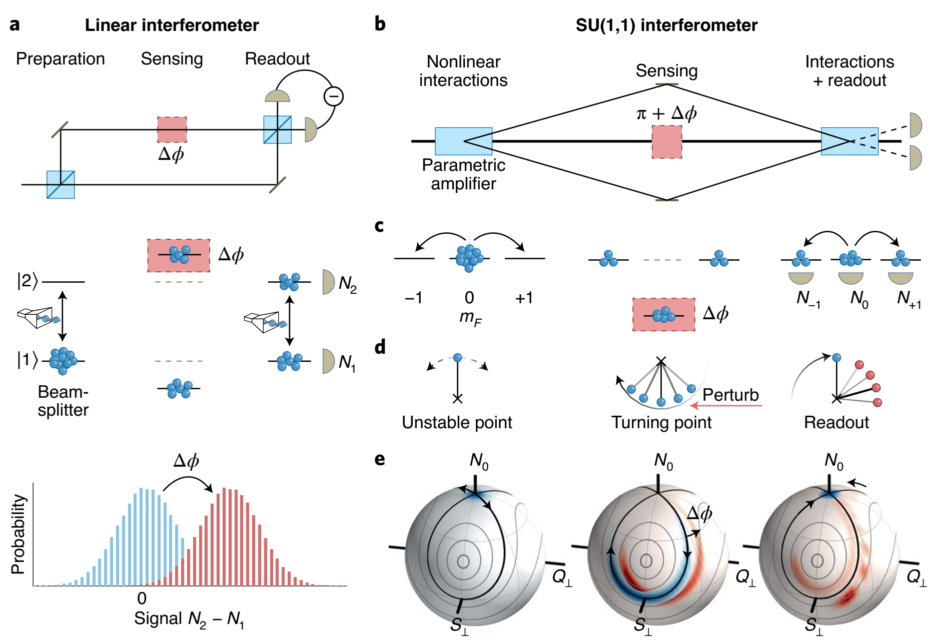

Fig. 1 | Linear and SU(1,1) interferometry. a, In a linear optical interferometer (top), an incoming beam (black line) is split into a superposition of two paths via a beamsplitter. A relative phase change between the two paths leads to a measurable imbalance after the second beamsplitter. The atomic analogue consists of an ensemble of uncorrelated atoms, each initialized in an equal superposition of two states with N_1 and N_2 atoms (second row). The states are chosen such that the field to be measured perturbs their energy difference, which translates into a phase difference $\Delta\phi$ after probing it for a certain time. To observe this signal, one applies a resonant radiation pulse that converts the acquired phase into a population difference between the two atomic states. For independent particles the precision of this phase measurement is limited by the width of the resulting binomial distribution (bottom). **b**, In an SU(1,1) interferometer, entanglement between the two arms is generated by a nonlinear crystal that is driven by a pump laser to produce correlated photon pairs. Disentanglement is achieved by a second nonlinear crystal driven by the same pump field with a specified phase shift. If the number of photons in the two arms is small compared with the pump field, all correlated photon pairs are reconverted into the pump mode if the phase shift is precisely π, whereas small perturbations in the phase lead to large changes in the side mode intensities. **c**, In Liu et al.[1], the atomic analogue of the SU(1,1) interferometer is realized within the spin-1 ground state featuring three magnetic sublevels: state $m_F = 0$ and states $m_F = \pm1$. After initializing all atoms in the $m_F = 0$ mode, collisional interactions convert pairs of $m_F = 0$ atoms into correlated atom pairs in states $m_F = \pm1$; the number of atoms in each state is denoted by N_{-1}, N_0 and N_{+1}. **d**, The dynamics are similar to an inverted quantum pendulum. Here, quantum fluctuations in the orientation and angular momentum of the initial state lead to a superposition of clockwise and anticlockwise motion. After a full oscillation period, the unperturbed pendulum returns to its initial state (blue), while small perturbations lead to deviations of the final orientation (red). **e**, The atomic dynamics are represented on a sphere, spanned by the population in N_0 and the transversal spin and quadrupole moment $S_\perp$ and $Q_\perp$, respectively. The initial quantum state is represented as a two-dimensional Gaussian distribution around the pole and subsequently spreads along the classical mean-field trajectories (black lines). Even a perturbation small compared with the initial quantum fluctuations, if applied halfway through the entangling evolution in the atomic gas, can be amplified into a large and readily detectable deviation in the final state.

evolution — the same interactions that initially entangle the atoms ultimately also disentangle them[1].

The measurement imprecision of a typical atomic sensor (Fig. 1a), consisting of an ensemble of uncorrelated atoms, scales as the inverse of the square root of the total number of atoms ($\sqrt{N}$). This limit, set by the independent quantum projections of uncorrelated particles, is referred to as the standard quantum limit. This limit can be overcome by employing an ensemble of entangled particles. Entanglement allows the probability distribution of measurement outcomes to exhibit narrower features than possible for an uncorrelated state. Thus, any change of the distribution is easier to detect, enabling the measurement imprecision to be reduced towards an optimal scaling as the inverse of the total number of atoms, known as the Heisenberg limit. In practice, however, the uncertainty caused by the noise of the detectors becomes more dominant as the features in the probability distribution become narrower. In the case of highly entangled states, this detection noise not only degrades the achievable sensitivity but can entirely eliminate any advantage gained from using entanglement.

The challenge of detecting a highly entangled state can be circumvented by applying a disentangling operation before detection. Variations of this principle have been demonstrated in contexts ranging from optical interferometry to spectroscopy with atoms and ions[2–5]. A canonical example in the case of optical interferometry is the so-called SU(1,1) interferometer[6] shown in Fig. 1b. Entanglement between the two interferometer arms is generated by a nonlinear crystal that is driven by a pump laser to produce correlated photon pairs in the two arms. Disentanglement is then achieved by a second nonlinear crystal driven by a pump field with the same intensity and the opposite phase.

Liu and colleagues realized an atomic analogue of the SU(1,1) interferometer using a Bose–Einstein condensate consisting of over 26,000 rubidium atoms (Fig. 1c). They prepared the atoms in the spin-1 ground state, featuring three magnetic sublevels that play the roles of the pump mode and the two interferometer arms. After initializing all atoms in the pump mode, they utilized collisional interactions to convert pairs of atoms in the initial state into correlated atom pairs in the states mimicking the interferometer arms. To achieve a Heisenberg scaling in phase sensitivity, a macroscopic fraction of the atoms needs to be converted into entangled pairs. As a result, the population of the pump mode is significantly depleted, which generically should lead to a failure of the disentangling operation. The solution to this problem is simply to wait — under the continued influence of collisional interactions — for the system to disentangle itself.

But why does the interacting atomic system ultimately return to its initial unentangled state? It turns out that, in the classical limit, the dynamics of the spin-1 Bose–Einstein condensate are similar to an inverted pendulum[7,8]. In the quantum mechanical description, quantum fluctuations in the orientation and angular momentum of the initial state lead the pendulum to fall into a superposition of clockwise and anticlockwise motion as illustrated in Fig. 1d. Irrespective of the direction of motion, the pendulum ideally returns to its initial position after a certain time. If, however, the quantum pendulum is slightly perturbed by an external field halfway through this evolution, then the final state may deviate dramatically from the initial state (Fig. 1e).

The use of cyclic dynamics in nonlinear interferometry offers a significant advantage over the original concept of SU(1,1) interferometry. In the earlier demonstration of an atomic SU(1,1) interferometer that the work of Liu and colleagues builds on, only 1% of the total number of atoms were converted into correlated atom pairs[4]. In contrast, in the present work, the full ensemble of atoms is used for entanglement-enhanced interferometry. So far, the metrological gain has been limited by experimental imperfections, including atom loss. Nevertheless, the nonlinear interferometer achieved a factor of three in metrological gain due to entanglement, meaning that three times as many unentangled atoms would be required to reach the same sensitivity. The demonstration of enhanced sensitivity via cyclic dynamics is so far a proof of principle, and has yet to be applied to a practical sensing application. An enhanced precision in magnetometry, for example, could be employed in applications of ultracold atomic gases to magnetic imaging of materials[9].

This method adds to a growing arsenal of protocols for entanglement-enhanced spectroscopy that harness interactions not only to generate entangled resource states but also to facilitate their detection[2,10]. A notable alternative to the use of cyclic dynamics is to implement the disentangling operation by reversing the sign of interactions, allowing the system to effectively evolve backwards in time towards its initial unentangled state[5,11]. One such protocol was recently applied to achieve a Heisenberg scaling in phase sensitivity[12]. Yet in many physical systems, reversing the sign of interactions is not possible, which makes the use of cyclic dynamics a potentially powerful alternative. This first demonstration leverages the symmetry of global interactions in a Bose–Einstein condensate to access cyclic dynamics. Recent discoveries of periodicity in the dynamics of more complex interacting many-body systems[13,14] open the door to generalizing the approach to a wider range of physical platforms. ❐

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Competing interests

The authors declare no competing interests.