QUANTUM SENSORS AND THEIR LIMITS

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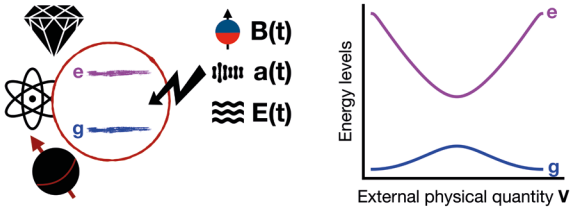

A fundamental aspect of quantum systems lies in their extreme sensitivity to external perturbations. This characteristic, which generally represents a considerable challenge for physicists seeking to isolate these systems in order to observe their quantum properties, can actually be transformed into an advantage. Indeed, this intrinsic sensitivity makes quantum systems ideal candidates for high-precision metrology. Quantum sensors exploit this susceptibility to measure physical quantities with precision difficult to match with classical approaches.

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To illustrate how quantum system and their interaction with the environment can be tuned for a given application, it is interesting to consider the example of the single-Cooper-pair box. Composed of a small superconducting electrode connected to a reservoir via a Josephson junction, the Cooper-pair-box constitutes an artificial two-level system that can be used as a qubit: the charge qubit. By controlling the exact configuration, particularly the ratio of Josephson energy to charging energy, this type of superconducting circuit can be made sensitive or unsensitive to charges, a characteristic directly observable in the transition energy spectrum as a function of the effective charge offset (see Fig. 1). While quantum information processing demands systems that are highly isolated from environmental noise to preserve quantum coherence, quantum sensors deliberately exploit their interaction with the environment.

In this context, it is interesting to precisely identify the important properties required for a quantum sensor. Quantum sensors constitute a specific class of measurement devices that exploit the properties of quantum mechanics to detect and quantify physical quantities. Inspired by DiVincenzo's criteria for quantum computers, Degen *et al.* [1] proposed that a quantum sensor is distinguished by four essential characteristics:

- (i) The system must possess discrete energy levels, a fundamental characteristic of quantum systems.
- (ii) It must be possible to initialize the system in a well-defined quantum state, generally the ground state or a specific superposition state.
- (iii) The system must be able to be manipulated coherently, thus allowing controlled quantum operations.
- (iv) The quantum system must interact with the physical quantity of interest V(t), and this interaction must modify the transition energy of the system, generally in a linear or quadratic manner.

These criteria define a conceptual framework that encompasses a wide variety of physical systems - from cold atoms to nitrogen-vacancy color centers in diamond, to Josephson junctions and superconducting qubits. It also becomes apparent that what

distinguishes quantum sensors from their classical counterparts is not so much their size or microscopic nature, but rather the exploitation of fundamental principles of quantum mechanics in the measurement process itself.

QUANTUM ADVANTAGES IN METROLOGY

Quantum sensors do not merely exploit the properties of microscopic systems; they take advantage of the very principles of quantum mechanics to achieve superior performance. Several fundamental advantages can be identified [1]:

- The quantization of energy levels offers an absolute reference for measurements, unlike classical systems that often require external calibration. Although not a sensor in the strict sense of the term, atomic clocks exploit the transition frequency between two energy levels of an atom, thus providing a time reference of remarkable stability. This is actually a quantum technology that we use daily since it is an integral part of the satellite positioning system.
- Quantum superposition allows for simultaneously exploring multiple configurations of the system. This superposition enables the implementation of quantum measurement algorithms, such as the quantum phase algorithm, which offer algorithmic advantages over classical approaches.
- Quantum entanglement allows for non-classical correlations between different parts of the measurement system, enabling the surpassing of precision limits accessible to classical strategies. This approach notably allows for surpassing the standard quantum limit.

Finally, the discrete nature of quantum interactions (for example, the absorption or emission of individual photons) allows in some cases ultimate sensitivity to extremely weak signals, up to the detection of single events.

FUNDAMENTAL LIMITS OF QUANTUM METROLOGY

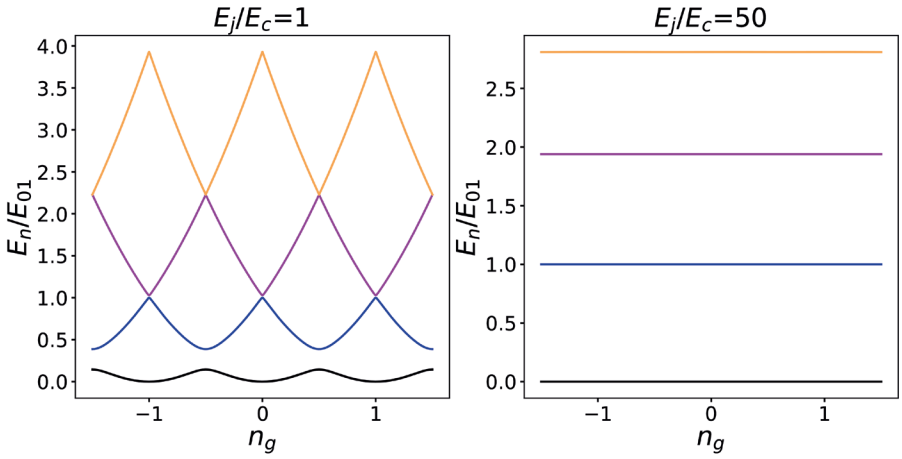
From a formal point of view, the precision of estimation of a parameter ϕ is bounded by the quantum Cramér-Rao inequality [2] by $\Delta\phi \geq 1/\sqrt{(n\,FQ)}$, where n is the number of independent measurements and FQ is the quantum Fisher information, which quantifies the maximum sensitivity achievable for a given quantum state. Due to the additivity of quantum Fisher information, an important fundamental limit follows directly from this inequality: the standard quantum limit (SQL) with a dependence on $1/\sqrt{n}$. This limit, known as shot noise in quantum optics, assumes nothing more than classical statistical correlations between different measurements. It therefore does not allow for fully exploiting the quantum nature of the system and probes. An obvious strategy to exceed this limit is therefore to use quantum effects such as entanglement to introduce correlations. Nevertheless, quantum mechanics still sets ultimate precision limits through Heisenberg-type uncertainty relations, which are sometimes referred to as Heisenberg bounds with a dependence on 1/n.

An emblematic example of the application of these concepts is the Advanced LIGO gravitational interferometer, designed for the detection of gravitational waves. In its initial configuration, this instrument operated at the standard quantum limit. The use of squeezed states of light allowed for redistributing the quantum noise between different complementary observables, thus reducing the noise in the quadrature of interest and allowing for crossing the SQL barrier over a wide frequency range [3].

ADVANCED QUANTUM STATES FOR METROLOGY

While the coherent state -- considered as the most classical-like quantum state -- present equal fluctuations for phase and intensity, squeezed states on the other hand can have much smaller fluctuation for one of the quadrature to the expense of the other (see Fig. 2). This reduction of the fluctuation is essential to overcome the SQL as it allows to greatly reduce the uncertainty for a well-chosen observable. Yet, while quantum squeezing allows for exceeding the SQL, other more sophisticated quantum states are better suited to approach the ultimate Heisenberg limit. ●●●

Figure 1. Transition energies for the first 4 levels as a function of the charge offset n_g, normalized to the 0 → 1 transition n_g=0 (E_{01}). The left panel illustrates the case when the charging and Josephson energies are equal, and the right panel illustrates the case when the Josephson energy is 50 times larger than the charging energy (transmon regime).



Among these, N00N states represent a particularly interesting example [4]. A N00N state corresponds to a quantum superposition of the form $|N,0\rangle + |0,N\rangle$, where N particles (typically photons) are simultaneously in one or the other of two possible modes. The metrological interest of these states lies in their increased sensitivity to perturbations: a N00N state accumulates a phase N times faster than a classical state containing the same number of particles.

To illustrate this phenomenon, let us consider an entangled two-photon state $|2,0\rangle + |0,2\rangle$ passing through a medium inducing a phase shift ϕ. While a classical two-photon state would acquire a global phase of $2\Delta\phi$, the entangled state develops a phase of $4\Delta\phi$, thus doubling the sensitivity of the measurement [5]. More generally, for an incident N00N state, the probability of finding the state $|N,0\rangle + \exp(iN\phi)|0,N\rangle$ is given by $q(\phi)=\cos^2(N\phi/2)$. The error on the phase is then obtained by $\Delta\phi=\Delta q/(\partial q/\partial\phi)=1/N$, the Heisenberg limit. This amplification of sensitivity constitutes the very signature of the quantum advantage in metrology.

PERSPECTIVES: CIRCUIT QUANTUM ELECTRODYNAMICS

A particularly promising platform for the development of advanced quantum sensors is circuit quantum electrodynamics (cQED) [6]. This approach, which transposes the concepts of traditional quantum electrodynamics to superconducting circuits, allows for extraordinarily strong and controllable light-matter interactions. In these systems, superconducting qubits play the role of artificial atoms, while superconducting resonators replace optical cavities. The decisive advantage of this architecture lies in the extreme confinement of electromagnetic fields, leading to couplings several orders of magnitude greater than in conventional optical systems.

These strong interactions facilitate the preparation and manipulation of non-classical quantum states, including squeezed states, large-photon-number Fock states, and even more complex states such as Gottesman-Kitaev-Preskill (GKP) states [7]. This ability to generate advanced quantum resources paves the way for a new generation of quantum sensors capable of operating at the fundamental Heisenberg limit. Recent work has demonstrated the use of displaced cat states, more robust than squeezed states or Fock states, with a sensitivity for phase and amplitude estimation very close to the Heisenberg limit [8]. Looking forward, GKP states are extremely promising in the context of quantum sensors as they are inherently resilient to photon loss. Furthermore, these states have been at the centre of important effort in quantum computing for their application in quantum error correction and protocols have already been successfully implemented experimentally. For quantum sensing, quantum error correction opens an interesting avenue as it would allow for maintaining complex quantum states that can approach the Heisenberg limit.

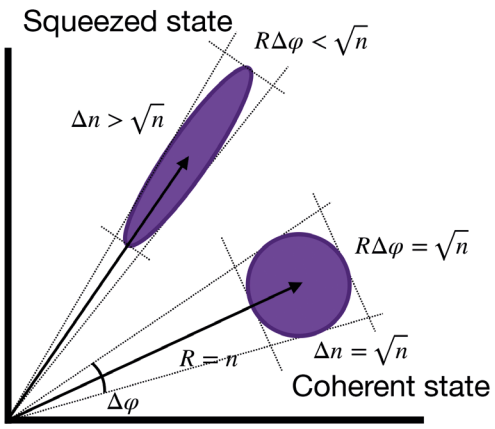


Figure 2. Phase-space diagram depicting the fluctuations, in photon number Δn and phase $\Delta\phi$, of coherent and squeezed states. While the coherent state has equal fluctuations in intensity and phase, the squeezed state can present decreased phase fluctuations at the expense of increased intensity fluctuations.

THE PRACTICAL DILEMMA: COMPLEX QUANTUM STATES VERSUS MULTIPLICATION OF CLASSICAL SENSORS

Examining only the fundamental limits of quantum metrology seems to suggest that the use of quantum sensors constitutes the best way to improve sensitivity. However, the fundamental question faced by experimenters is that of the compromise between complexity and the real cost-benefit of advanced quantum approaches. On one hand, theory clearly demonstrates that a sensor using N resources in an optimal quantum state can achieve a precision proportional to 1/N, surpassing the classical limit of $1/\sqrt{N}$. On the other hand, this theoretical improvement must be weighted by the considerable technical challenges associated with the preparation and maintenance of these quantum states, which are often extremely fragile. The N00N state is a perfect example: although it does indeed allow reaching the Heisenberg limit, this type of state is particularly sensitive to losses, making its practical use very difficult. In general, the production of large non-classical states requires sophisticated experimental setups (indistinguishable photon sources, low-loss optical elements, cryogenic environments) and generally suffers from a success probability that decreases exponentially with N. In parallel, a classical approach simply consisting of multiplying the number of independent sensors by a factor of N^2 would effectively achieve the same metrological precision as an optimal quantum sensor using N resources. This brute force strategy has the advantage of being technically simpler to implement and of increased robustness to noise. In many current practical cases, the distributed classical approach remains competitive, even superior, due to its technological maturity. However, in contexts where resources are inherently limited (spatial, energy, or material

availability constraints), or when quantum correlations offer unique capabilities (such as interaction-free detection), the quantum approach retains a decisive advantage that justifies the considerable efforts to prepare, control, and maintain quantum states. Furthermore, integrating quantum error correction would provide more robust quantum resources for sensors operating at the Heisenberg limit. With recent advances in research laboratories, the frontier of this competition is gradually shifting towards quantum solutions that clearly surpass their classical counterparts.

CONCLUSION

Quantum sensors represent an exciting frontier at the intersection of fundamental physics and precision technologies. On one hand, the use of a system with discrete energy levels allows for developing absolute sensors, which therefore do not require calibration. This aspect is at the center of important efforts to determine more precisely the base units of the International System of Units. On the other hand, the laws of quantum mechanics allow for controlling correlations in such a way as to surpass the standard quantum limit, thus offering an enormous gain in sensitivity. The development of quantum sensors could consequently greatly impact fields as diverse as gravitational wave detection, medical imaging, inertial navigation, or geological prospecting. Recent advances in the generation and manipulation of non-classical quantum states, particularly in platforms such as circuit quantum electrodynamics, also suggest metrological applications operating at the fundamental limits allowed by physics. The main challenge, however, remains preserving the fragile quantum properties in the face of decoherence while maintaining the necessary interaction with the quantities to be measured. Meeting this challenge requires interdisciplinary approaches, combining quantum physics, materials science, and precision engineering.

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