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Bridging Fundamental Physics and Practical Applications: Advances in Quantum-Enhanced Sensing

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Abstract: Quantum-enhanced sensing has emerged as a transformative technology with the potential to surpass classical sensing modalities in precision and sensitivity. This study explores the advancements and applications of quantum-enhanced sensing, emphasizing its capacity to bridge fundamental physics and practical implementations. The current progress in experimental demonstrations of quantum-enhanced sensing systems was reviewed, focusing on breakthroughs in metrology and the development of physically realizable sensor architectures. Two practical implementations of quantum-enhanced sensors based on trapped ions were proposed. The first design utilizes Ramsey interferometry with spin-squeezed atomic ensembles, employing laser-induced spin-exchange interactions to reconstruct the sensing Hamiltonian. This approach enables measurement rates to scale with the number of sensing atoms, achieving sensitivity enhancements beyond the standard quantum limit (SQL). The second implementation introduces mean-field interactions mediated by coupled optical cavities that share coherent atomic probes, enabling the realization of high-performance sensing systems. Both sensor systems were demonstrated to be feasible on state-of-the-art ion-trap platforms, offering promising benchmarks for future applications in metrology and imaging. Particular attention was given to the integration of quantum-enhanced sensing with complementary imaging technologies, which continues to gain traction in medical imaging and other fields. The mutual reinforcement of quantum and complementary technologies is increasingly supported by significant investments from governmental, academic, and commercial entities. The ongoing pursuit of improved measurement resolution and imaging fidelity underscores the interdependence of these innovations, advancing the transition of quantum-enhanced sensing from fundamental research to widespread practical use.

Keywords: Quantum-enhanced sensing; Medical imaging; Standard quantum limit; Ramsey interferometry

1 Introduction

Quantum-enhanced sensing is an exciting area of research, where nano scale quantum technology could be used to advance practical applications in sensing and imaging. Development in this field has been quick, since the advent of the quantum standard for atomic clocks in the mid-2000s. Consequently, there is potential for a second quantum revolution in consumer electronics, telecommunication, drug chemistry, and medical imaging. This study presents a recent theoretical understanding of current quantum sensors, not only exploring the potential benefits of using pure-qubit sensors but also addressing issues associated with their practical implementation [1, 2].

In a wider context, the strong interrelation between fundamental and applied science—namely between physics and engineering—necessitates a conceptual leap. It is essential to change the near-exclusive focus on developing quantum technology to rather than develop a quantum intuition. In the case of quantum theory, this requires pedagogy and research to be altered. Today, the challenge lies in making manufactured sub-parts more affordable instead of developing new imaging systems. As quantum technologies are driven directly by cutting-edge fundamental research, the exploitation naturally reflects the interests of the relevant stakeholders [3].

The use of entangled quantum states to enhance measurements of an unknown parameter has been a fruitful area of interdisciplinary research over the last few decades. These developments were reviewed with a focus on sensing applications. The transfer of quantum information and the resulting interference effects were explored, as originally pointed out. Recent efforts in four areas of active research were highlighted. Many-body atomic probes interacting with light in optical lattices can be modeled with circuit-quantum electrodynamics (QED) Hamiltonians, where the exchange of quantum light between the atoms and the microwave field has sensitively affected the many-body state of the system. This has led to the realization of quantum light generation and amplification, as well as new avenues for engineering many-body coherent dynamics and multicode quantum states. Advantages of collective properties in many-body quantum sensors have been demonstrated, particularly in the context of quantum non-demolition (QND) measurement protocols. Fundamental limitations arising from sensor static noise have been shown to depend significantly on the distribution of the input state [4, 5].

1.1 Background and Motivation

The next-generation precision sensor technology is essentially what quantum sensors are. By taking advantage of quantum phenomena such as superposition or entanglement, quantum sensors can provide measurements that are more accurate than what is possible with scaled-up conventional sensors. Due to their ability to probe the territory of fundamental physics, this emerging technology has drawn great interest from the scientific community and industries across different fields [6]. Moreover, the robustness of these systems, rooted in both physical and engineering principles, enables the detection of small forces while minimizing susceptibility to artifacts. This remarkable feature grants the opportunity to comply with standards and employ probes with exceptional quality. Quantum-enhanced sensor technology has three core applications: portable/remote sensing, interrogating fundamental physics, and sensing beyond the classical limit [7].

Portable or remote sensing scenarios have sparked interest in the semiconductor industry, as the ultimate goal is to build a stand-alone quantum technology compatible with a microchip configuration that can be economically manufactured. While much progress has been made in real-life applications with solid-state spin defects, in particular nitrogen-vacancy (NV) centers in diamond and silicon carbide, cooling down to liquid nitrogen temperature and optical setups are still required, which prohibits portable sensing. Quantum technologies, such as superconducting qubits or charged quantum dots, would be challenging to implement in this respect because of their larger size and extreme fabrication requirements [8, 9].

Quantum mechanics is a fundamental theory and, at the same time, is the underlying physical framework of many currently evolving technologies, including quantum information and quantum sensing. This study tries to untap the potential of quantum-enhanced measurement technologies by presenting the essential basics of quantum mechanics that are relevant to sensing. Quantum mechanics is a physical theory used to describe the behavior of very small particles on extremely small scales [10].

Wave-particle duality can be demonstrated in various ways. One of them is an experiment where a stream of light passes through a mask that contains two very narrow, close parallel slits. The light is a wave that can spread into each available dimension, including the dimension perpendicular to the propagation direction. After passing through the two slits, one of a few things happens. The waves coming from the two slits either superpose or extinguish each other depending on the difference in distances they have traveled before meeting again, forming an interference pattern. The uncertainty principle states that, for some combinations of observable properties of a particle, such as the particle's location and momentum, it is fundamentally impossible to exactly measure both properties at the same time. Predictions of classical physics, in particular Newton's physics, probably initiated in such a way that one could obtain them from cramming over arbitrary simple assumptions and generalizations. Furthermore, the law of causality is embedded. That is, each moment of time is a result rather than a cause. Such determinism is not useful in the microscopic world once it was suggested that properties of particular objects could preferentially cause various aspects of the sensor processes. It was stated that "God does not play dice." Measurements only show the probability that a given event will happen [5]. However, in quantum theory, this is reversed, greatly surprising many scientists at the time and even now.

The need to develop a quantum-enhanced sensor acts on its own drive: the quest for finding or building a quantum sensor continues to unveil the laws of fundamental physics. The next best candidates to observe exotic interactions are dark matter axions, gravitational forces from extra spatial dimensions, and searching for signals from quantum space-time collapse models. Detecting these tiny forces is impossible with conventional sensors since they can be hidden inside complex backgrounds (e.g., solar and galactic). However, by using quantum systems whose dynamics can be entangled, interactions can be magnified and detected beyond the classical limit.

2 Fundamental Principles of Quantum Sensing

The concepts of coherence, uncertainty principle, and wave functions are fundamental to the understanding of quantum mechanics and play key roles in the quantum-enhanced feature of sensors. Coherence is commonly associated with the unsustainable brightness of lasers. However, more generally, coherence implies a particular structure of the quantum states of a light field [9]. As an alternative picture of coherence indicating resource for quantum-enhanced precision measurement, a simple two-mode squeezed vacuum state has been presented. The uncertainty principle, by which it is understood that the exact determination of the position of a quantum system would drastically enhance its ability to measure the conjugate momentum, is one of the essential concepts in quantum mechanics [6]. Gaussian wave packets, which are of broad applicability, focusing on how they behave under spreading and translation, are core quantum states that are significant for understanding the quantum-sensing proposal.

Such a core part collects the essential theoretical basis for a coherent understanding of the basic principles involving both optical fields and atomic systems. It also includes discussions on fundamental quantum principles, such as quantum states, measurement, noise analysis, quantum entanglement, and quantum frequency conversion, which import disciplines from quantum optics and quantum information science into quantum-enhanced sensors. Limitations on the precision of classical sensors, quantum-classical boundary, and fundamental limitations on the performance of quantum sensors based upon various types of resource states such as squeezed states and cluster states were well-reviewed [11].

The goal of nearly all forms of scientific inquiry is to make a measurement. Indeed, measurement is a fundamental physical concept; many of the most important ideas about the physical world in this study were ascertained by testing hypotheses through measurement. These measurements come in all shapes and sizes, ranging in scale from neutrino experiments that stretch across entire continents to atomic clocks that take up less than a cubic inch of space. They were used to measure length, duration, magnetic field, and nearly any physical quantity one can think of. The techniques used to make these measurements are as broad as the systems they are used to probe. For example, interferometry, which is generally used to measure phase, has innumerable applications from determining the size of the planet Jupiter to the size of quantum vacuum fluctuations. Without probes to make sense of the world around us, people's fundamental understanding of the world that they live in would be greatly diminished.

2.1 Quantum Mechanics Basics

Quantum mechanics recognizes that the world on a very small scale behaves according to fundamental concepts that differ significantly from those applied to macroscopic objects. A remarkable feature is that quantum objects possess wave- and particle-like properties at the same time. This concept is usually referred to as wave-particle duality. For large objects, the existence of a solid boundary between wave- and particle-like properties is maintained. In contrast, for very small objects, this boundary disappears and wave-particle duality comes into play for all objects. Wave-particle duality was first indicated in the early 1900s by de Broglie, experimentally confirmed in the double-slit experiment, and mathematically expressed in the framework of quantum mechanics [6]. Another remarkable feature is the uncertainty principle proposed by Heisenberg. The uncertainty principle establishes fundamental limitations on the precision with which pairs of quantities (observables), such as position and momentum, can simultaneously be known. The limits stem from the wave-like properties of objects: localized states in one entity space, such as position space, necessitate spreading in the corresponding canonical dual entity space, such as momentum space [12, 13]. Simply put, the more accurately the position of a quantum object is known, the less accurately its momentum (speed) can be known, and vice versa.

Such a mixture of wave- and particle-like properties occurs also for macroscopic measurement instruments that detect quantum objects. When a quantum object approaches a measurement instrument, the wave function of the quantum object spreads into a superposition of different outcomes [14]. Therefore, a measurement that determines one outcome and results in changing the state of the quantum object takes place. Afterwards, the quantum object behaves classically, and its wave-like properties are erased. The act of measurement is thus one of the fundamental phenomena of the world governed by quantum physics. Measurements are essential for coping with the physical world and gathering information about it.

Figure 1 depicts various atom technology platforms. Subgraph (a) of Figure 1 shows adjustable interacting atoms. At the top, an appealing square well potential helps to clarify the physical significance of the scattering length. When $a < 0$ (left), the wave function has no zeros on the $r > 0$ plane. For $a > 0$ and $k < 0$, there are three zeros in the $r > 0$ plane. As seen in $a < 0$ (right), the Yukawa model's bound state is defined using quantum mechanics. The Fano-Feshbach magnetic resonance mechanism, shown on the bottom left, is used to determine the energy difference between the open channel threshold and the bound state in the closed channel by altering the static magnetic field. The tabulated values of the scattering length versus magnetic field are given in the bottom right of the figure.

Subgraph (b) of Figure 1 discusses optical lattices in a tutorial fashion, showing how 1D, 2D, and 3D geometries provide 2D, 1D, and 0D confinement, respectively.

In Subgraph (c) of Figure 1, a linear Paul trap is used as an example to demonstrate labeled ions. The confinement is held together by static electric control fields and time-dependent radio frequency oscillating electric fields. A linear string is formed by laser-cooling ions contained in a strong radially confining potential, similar to a tight string (inset image of eight ions), with the spacing reflecting a balance between external confinement and Coulomb repulsion [9].

Subgraph (d) of Figure 1 depicts the Rydberg atoms. To the left, there are the Rydberg atoms: atoms placed into very high energy levels. On the right side, the idea of Rydberg blockade is mentioned there because they have such strong interaction that a doubly excited state is pushed out of resonance. It can be seen in the center; if two Rydberg atoms are closer positioned than the corresponding blockade radius rb, it is improbable.

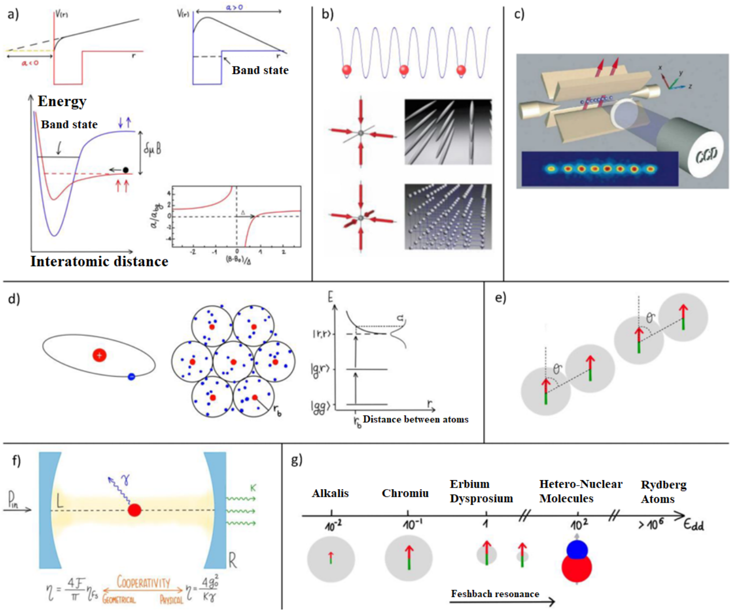

Figure 1. Various atom technology platforms, (a) Adjustable interacting atoms, (b) Optical lattices in a tutorial fashion, (c) Linear Paul trap, (d) Rydberg atoms, (e) Interaction of bipolar atoms, (f) Atomic system in optical cavities, (g) Energy scale including IF and FF resonances [2]

Subgraph (e) of Figure 1 shows the interaction of bipolar atoms. The electric fields of bipolar atoms can be signified as dipoles. The interaction is inherently anisotropic, as described in the 1D example where a rotation of the angle θ between the dipole direction and the direction in which atoms align can switch the interaction from maximally repulsive (head to head) to maximally attractive (head-to-tail).

Subgraph (f) of Figure 1 shows the atomic system in optical cavities. The free-space cooperatively $\eta f s$, related to the atom-photon strength $g20$, is increased by factor $\eta = 4F\eta f_s/\pi$ due to the number of round trips of the photon in the cavity, where F is the free-spectral range. The system is open and out of equilibrium because of photon loss characterized by a rate κ and atomic spontaneous emission characterized by a rate γ. As shown in the figure, $\eta = 4g20/(\mathrm{Kz})$, and thus $g20$ can be adjusted geometrically.

Subgraph (g) of Figure 1 shows a review of the energy scale, including IF and FF resonances, dilute systems, dipolar to hetero-nuclear to Rydberg gas samples.

2.2 Quantum Superposition and Entanglement

The phenomena of quantum superposition and entanglement lie at the core of many imaginative applications for individual quantum systems. Though these phenomena have no classical-like counterparts, they possess unique properties that enable a variety of powerful applications [12]. A composite system may be in a state that cannot be expressed as a product of states assigned to its individual components. For example, consider a pair of spins that can be described as follows:

$$|\Phi\rangle = 1/\sqrt{2}(|\uparrow\rangle 1|\downarrow\rangle 2 - |\downarrow\rangle 1|\uparrow\rangle 2 \tag{1}$$

Any description that allows for individual assignments of states to both spins is incomplete because it ignores the essential non-factorable correlations. This is the hallmark of quantum entanglement [6]. Entangled states with other degrees of freedom (e.g., photonic polarization states) are possible. Entanglement is a global property and has no classical equivalent. In contrast to classical correlations, such as those bygone variables bound by the Bell inequalities or probabilistic distributions, entanglement gives rise to stronger correlations, allowing for assignments that are incommensurable in terms of classical-like descriptions [12].

3 Quantum Technologies in Sensing

This section discusses quantum technologies that enable quantum-enhanced sensing to emerge. It covers both the devices and the necessary tools. Several quantum metrology platforms and quantum detectors of non-quantum sensor (QS) properties were discussed. Bosonic squeezing allows precision measurements of bosonic quadratures, improving the signal-to-noise ratio (SNR) for classical signals [6]. Alternatively, non-classical bosonic states can improve single-photon detectors. Non-Gaussian filtering removes noise with minimal signal distortion for classical light sensors. Non-classical qubit filters improve SNR and information extraction in quantum light detectors compared to their classical counterparts [15].

Quantum metrology is often bound to reach the quantum Fisher information matrix (QFIM)–the fundamental limit–for silent and non-interferometric precision measurements. At the QFIM limit, the precision bounds coincide with those given by quantum positive operator valued measures (POVMs). The advancement in many-body physics has allowed for more efficient exploration of measurement protocols. Activating qubit non-classical correlations improves non-interferometric estimation of a parameter by inducing on-qubit rotations sensitive to it [16].

3.1 Quantum Sensors and Detectors

Quantum sensors and detectors are key components of quantum-enhanced sensing systems. These devices leverage the quantum nature of light or matter to perform high-precision measurements in the presence of noise and other imperfections that limit the performance of classical sensors. Quantum detectors exploit the non-classical correlations inherent in quantum systems to enhance measurement sensitivity beyond the SQL. Entangled photon pairs generated by a quantum light source can be employed to perform quantum detection of light at the SQL [6]. The basic working principle of a quantum-enhanced detector involves the generation of non-classical states of light (entangled photon pairs) using a quantum light source. Light of lower intensity than shot-noise illumination is detected while its non-classical correlations are exploited to reduce the uncertainty in the measurement. Quantum detectors apply a two-photon interference technique known as Hong-Ou-Mandel interference combined with photon number-resolving detection. This study also highlights the prospects for translating the current proof-of-principle laboratory demonstration of quantum-enhanced photodetection to fieldable devices suitable for marine or terrestrial autonomous sensor networks [17].

This study also highlights a basic working principle of quantum sensors, where a quantum system, such as an atom, vacancy in a diamond, or superconducting circuit, interacts with a constant external effect, such as a magnetic field or temperature. Typically, classical sensors employ a classical measurement strategy that can involve continuous readout or repeated cycles of measurement and feedback to estimate the constant external effect. This study also describes quantum technologies in detecting electromagnetic (EM) radiation, including nano-Kelvin experiments using superconducting qubits, optomechanical dark spot arrays, and high-temperature superconductors. In nano-electronic qubits hybridized with quantum circuits, a carbon nanotube can be assembled in a state of low-frequency quantum mechanism.

3.2 Quantum Metrology

Quantum mechanics offers an array of counterintuitive phenomena that can be harnessed in various technological settings. For example, the ability of quantum systems to exist in a superposition of states lies at the heart of quantum computing, while the tailoring of correlations across quantum systems in complementary bases translates into the secure distribution of cryptographic keys. Quantum metrology, or the estimation of unknown parameters exploiting the peculiar properties of quantum systems, is as promising and opens the way to master technologies that would be infeasible otherwise. Some widely investigated quantum systems to develop quantum sensors are trapped ions, neutral atoms, superconducting circuits, NV centres in diamond, and photons [18]. As the name suggests, metrology refers to a measurement-related topic with broad implications in science and technology. Quantum metrology has been great in observing a precise quantity such as the time a system spends in an external potential in the position of literature. First derived using simple Hamiltonian, a lower sensitivity bound for sinusoidal magnetic field was calculated, understanding how quantum resources can improve sensitivity, especially in the fundamental interrogation time lying higher than one second. Quantum-enhanced measurements make use of quantum mechanical effects that can potentially provide ultra-precise estimates of physical variables [19, 20]. Such measurements have fundamental implications and can lead to the development of consumer technologies such as ultra-precise magnetometers for measuring the magnetic field of the Earth, frequency calibration of atomic clocks, detectors of gravitational waves, etc.

4 Applications of Quantum-Enhanced Sensing

Conducting and presenting research on quantum technologies, such as quantum-enhanced sensing, is invariably considering immediate and future applications. In this respect, the huge market for sensors is encouraging ground-breaking research to be focused on emerging technologies using quantum principles to enhance applications such as imaging, interrogation of objects and probing fields. It is envisaged that establishing a competitive edge in novel, technology-enhanced industrial sensors can lead to the strengthening of the national capability of the UK and the creation of jobs in design, implementation and manufacture [9, 21].

In addition to healthcare applications, the discussion on the market potential of quantum sensing technologies includes environmental monitoring. Several quantum technologies have been considered, such as quantum magnetometers—both room temperature and cryogenic ions, and novel quantum systems based on light, energy loss and mass for chemical sensing. The ambition is to develop these new sensors to a stage where they can be either mass produced or at least built as dedicated devices to replace benchtop optical devices currently used in laboratories. The overlap of quantum-enhanced sensing with philanthropic environmental issues, so much in the hearts and minds of the public, is likely to kindle longer-term partnerships than with more commercially driven technologies [22].

4.1 Medical Imaging and Diagnostics

Medical diagnostic techniques span a large number of modalities, including imaging techniques such as magnetic resonance imaging (MRI), computed tomography (CT) scans, positron emission tomography (PET), ultrasound imaging (USI), optical coherence tomography (OCT) and blood glucose level detection techniques based on capillary blood sampling. From a purely imaging perspective, the detection techniques can be broadly classified as either EM (e.g., CT, MRI, PET, OCT, etc.) modalities or a non-EM modality (e.g., USI). EM techniques rely on the absorption, transmission, reflection or other interaction of photons with a tissue, while USI techniques rely on the piezoelectric properties of a tissue in conjunction with the propagation properties of sound [10].

Most current medical imaging and diagnostic devices are based on the conventional sensing principles of these modalities. However, the use of quantum-enhanced sensors can provide additional degrees of freedom and advantages. In optical imaging modalities, the number and/or spatial distribution of photons carrying the imaging information in a thick dielectric medium can be exploited with quantum technologies to mitigate fundamental physical limitations imposed by the detection techniques. For example, given the non-ballistic and diffusive nature of the propagation of an optical signal through tissue, achieving the optical parametrically amplified spontaneous emission (OPASE) distribution can enhance the SNR by more than three orders of magnitude compared to the conventional Poissonian distribution illumination with the same average power [22, 23]. Moreover, the use of heralding detection schemes can enable the detection of images totally inaccessible to any classical devices [24]. Another quantum probing approach is to exploit narrow-band and entangled photon pairs produced from spontaneous parametric down-conversion or four-wave mixing processes. These have been shown to allow enhanced imaging resolution compared to their classical counterparts in mainly ballistic imaging scenarios. Interestingly, apart from solar oceans or turbidity distributions, imaging through planar interfaces (smooth and structured) would be a common diffusive scenario for diamond and physiologic media in the near infrared spectral range.

4.2 Environmental Monitoring

4.2.1 Applications of quantum-enhanced sensing

Quantum sensing and quantum-enhanced sensing techniques offer the potential for new precision measurement tasks. In the case of sensing, the focus is primarily on estimating parameters that describe the system. The use of quantum techniques offers a range of advantages over classical counterparts and has potential applications in a number of domains. The precision increase offered by quantum sensing can enable new directions of study in fundamental physics, as well as significant technological advances in fields as diverse as magnetometry, biology, secure communication, and navigation [25].

There is an increasing void between quantum sensing experiments aimed at closing a loophole in the Einstein-Podolsky-Rosen (EPR) criterion and the precision required in practical sensing or field estimation experiments. Some of the best-known quantum sensing and field estimation experiments use magnetic field estimation as a benchmark [26]. A number of key experiments that showcase quantum-enhanced sensing techniques and applications include motional state preparation for Ramsey interferometer guidance, a dual-Sagnac-phase atomic interferometer magnetometer, sub-femtotesla magnetometry using a k-space clock transition probe, and a sub-femtotesla multichannel image-vector magnetometer implemented in a quantum oscillator [27]. These experiments provide insight into how quantum techniques have solved specific research obstacles and opened up new directions. In all of the cases presented, the quantum sensing experiments have provided greater accuracy than the corresponding classical methods and pushed the limit of what is possible with state-of-the-art field sensing techniques.

To take a very simple example, quantum sensing may improve deduced trajectories in noisy navigation data provided by satellite networks, dramatically improving the abilities of autonomous vehicles or drone microelectromechanical system (MEMS) inertial navigation systems. For this reason, quantum-enhanced sensing is a priority in initiatives. The rapid acceleration of platforms in quantum sensing is also promising for many practical applications in which minimal space, cost, and resources are necessary to operate at the desired accuracy.

4.2.2 Quantum sensing in precision measurement

A great deal of research and development in the field of quantum sensing focuses on precision measurement. The importance is twofold: having better sensitivity and going below what is classically possible on larger scales, which is beyond the reach of quantum computing. There are numerous systems that show improved metrology performance. Ultra-high precision clocks are used in satellite navigation systems and to test for variations between fundamental constants. Atomic clocks rely on measuring the hyperfine ground state splitting of a trapped atom via a pulsed spectroscopy technique. They employ over 100,000 quantum particles confined in triangular optical lattices.

The Allan deviation reaches a minimum of 2.0×10^{-17} at an integration time of 4.0×10^3 s [28, 29]. Dynamical decoupling protocols for quantum memory techniques in solid-state nuclear magnetic resonance use a combination of composite decay and Uhrig dynamical decoupling with $\alpha = 1.0$ for an echo of 3.3 ms coherent evolution. In situ quantitative measurements of dark matter in the underground liquid-xenon detector, the use of a dual-phase technique allows for more precise height calibrations, which in turn improve position reconstructions and favor coilpack stability. Blade clocks, which have the same working principle as atomic fountains but are smaller in volume, can achieve stability down to 2.5×10^{-16} [20, 22]. In terms of medical imaging performance in diagnosing and monitoring patient conditions due to the superior contrast of speculative technologies, such devices probe magnetic fields induced by nuclear interactions in living tissue.

5 Challenges and Limitations

Quantum sensors have emerged as a transformative technology that can exploit quantum coherence to enhance the sensitivity and precision of measurements. They are becoming an established technology that creates new opportunities for precision sensing across the breadth of science [24, 25]. However, current quantum sensing technologies still present limitations that affect their applicability, ranging from the requirement of adapting the sensing strategy to the parameter of interest (which is thus unknown) to the fragility of the metrological resources. Even state-of-the-art platforms like trapped ion systems face challenges, such as low sensor connectivity and other factors, that may prevent them from approaching the best metrics [3, 14].

Fundamentally, it is known that, beyond a conventional limit set by the SQL with N identical probes, it is possible to exploit quantum correlations to achieve an enhanced rate of contraction of the estimation uncertainty with N (i.e., the so-called Heisenberg limit scaling as square root of N). On the other hand, one would like to achieve the opposite, i.e., use as many resources as possible to scale up the network performance and preserve the fundamental metrological sensitivity. Regrettably, most of the schemes explored so far rely on the distributed nature of the nodes and, as such, limitations coming from the protocol itself [11, 30].

5.1 Noise and Decoherence

In quantum-enhanced sensing, the precision of the measurement is limited by the back action of the measuring device on the measured system. This back action takes the form of noise, which also builds on the fact that decoherence destroys any potential advantages offered by quantum technologies. There is proliferating interest in experimental and theoretical proposals to exploit quantum information resources to enhance parameter estimation precision beyond the capabilities of classical sensors. However, proper systems and implementation to bridge fundamental physics with such applications and technologies have been somewhat lacking. The noise is not just technical noise, but all physically relevant processes that induce decoherence to the measured system. As decoherence is universal and ubiquitous, any realistic sensor accidentally suffers from all these noises, resulting in an abrupt performance drop, as shown, for example, in Heisenberg-limited sensors [11]. Because of such an exponential sensitivity drop, this directs to the study of noise-resilient schemes and exploring alternative resources such as dissipative states under noisy environments [31, 32].

The most common and universal type of noise is decoherence which could be caused by dephasing, decay, collective, or individual opening. In classical sensors, common modes of noise are used to mitigate such effects, including Kalman filters and associated optimal control protocols. To detect weak signals, the resulting output information is often subjected to complex signal processing steps utilizing such noise mitigation procedures. In quantum-enhanced sensing, noise would play the most destructive role as it not only builds on classical technical noises but also destroys any quantum informative resources that fundamentally enhance the sensor on top of classical noise. However, there have been recent noteworthy studies showing that noise could be cleverly engineered to enhance the sensing performance [24, 25].

5.2 Scalability

Adapting quantum-enhanced devices to existing infrastructures presents significant technological, economic, and logistical challenges. At present, the integration of quantum-enhanced devices into sensing architectures is largely limited to a single type of quantum device or the combination of classical technologies with quantum devices, predominantly at the single-photon level. Scalability in both device performance and laser system design must be tackled [21, 33].

6 Future Directions and Emerging Trends

Looking towards the future, many exciting directions for quantum-enhanced sensing can be foreseen. Several core technologies are on the brink of quantum-equivalent enhancement. Optomechanical sensors are becoming increasingly refined. They rival classical sensors at room temperatures and are being developed at the quantum-classical limit at cryogenic temperatures [2]. Semi-conductor spin sensors can extract single-agent information about the surrounding magnetic noise and have broad potential applications in biology, materials, and chemistry. Eyewear magnetoencephalography systems can be combined with machine learning to create ultra-low-cost quantum-enhanced sensing networks. Additionally, many sensing capabilities could be enhanced or newly developed for integration into quantum-embedded technology. Quantum-censors like Lidar or global navigation satellite systems could be enhanced via access to quantum resource pools. Such pools would ensure asymmetric versions of protocols like time-adjusted quantum key distribution or time-lock encryption. Finally, quantum-enhanced sensor nodes could be embedded into quantum networks that link advanced quantum sensors with quantum communication technology to protect them against undesired interactions and maintain integration over vast distances [22, 27].

Furthermore, quantum-enhanced sensing would now benefit from broader access to near-term quantum computers, with an increasing number of start-ups focusing on these hybrid devices. These considerations would imply that quantum machines should be combined with artificial intelligence for better autonomous task execution, improved classification of sensors and information extraction, and more sophisticated protocol implementation than is achievable today. Early efforts have already been reported in the literature, and the integration of quantum machine learning (QML) and sensing is likely to dominate future efforts in the field [6, 23]. Such combinations would ensure that the global impact of quantum-enhanced sensor nodes and networks would have a far-reaching influence on science and society.

6.1 QML in Sensing

The convergence of quantum computing and machine learning for sensing applications is expected to be of great relevance in the near future. QML algorithms and computers have recently been developed that could be used to revolutionize data analysis, pattern recognition, and decision-making in sensing systems. Quantum-enhanced processing of data collected by quantum sensors could optimize the performance of quantum-enhanced sensors, revealing unobserved states of the environment and enabling new predictive capabilities. Recent advances and future prospects in QML algorithms and quantum-enhanced machine learning for sensing applications may be highlighted, demonstrating how these technologies can improve the extraction of information about the environment from collected datasets and how they can bridge the gap between fundamental physics and practical applications [19, 33].

The recent remarkable improvements in quantum processors have led to an increased effort in exploring the use of quantum information technologies, including quantum computers and quantum sensors, for scientific and commercial applications in fields such as physics, chemistry, material science, and finance. For such applications, it is important to stress that the quantum advantage over classical approaches should be guaranteed. The achievement of a quantum advantage strongly depends on the nature of the data being produced at a quantum level [34]. If the input data follow classical distributions, standard classical machine learning approaches can be successfully applied with no loss of performance. Experimentally accessible quantum states, however, happen to be a remarkable resource when they are nonclassical and violate some form of a Bell-type inequality. For this data distribution, questions such as to what extent experimentally accessible quantum states are in contradiction with the classical world. If they can be certified as quantum, or if they are entangled or possess some form of negative classical correlation, they may be addressed with enhanced performance using QML [14, 35].

7 Conclusion

A prominent example of quantum-enhanced sensing is the utilization of polarizing beamsplitters (PBSs) in a cold-atom gravimetry setup, analyzed through a global unitary transformation. The system consists of N particles of two-level atoms interacting with EM fields, described as a polarized half-coherent thermal state. The PBSs convert the phase shift into correlators among the idler modes, allowing the observer Alice to measure the field in the photon-number (Fock) basis, thereby gaining information about the shift. Improvements in precision are achieved as the number of copies is increased, indicating a sharp transition from Poisson-like behavior to super-Poisson-like variance. This analysis features standing waves, shocks, and a precise conversion of a phase to the internal-excitation representation, enhancing the phase finding reciprocally to the initial thermal limit.

Entanglement is a key resource often utilized to improve sensitivity beyond classical limits. Testing for correlations among particles permits the reconstruction of the (local) Hamiltonians governing the initial dynamics, regardless of them being classical, quantum, or mixed [1]. For sensing situations, usually a unitary transformation is performed over the state (and sensor), e.g., a phase-shift operator associated with some system of interest, concluding that the sensitivity is determined, at fixed prior uncertainty, by the smoothest target distribution that permits the evolution of the state. This sensitivity can be quantified through measurements performed either before or after the interrogation phase.

Quantum technologies have attracted considerable attention in recent years due to their potential for revolutionizing navigation and timing. Today, the Global Positioning System (GPS) and other similar location services based on a large network of atomic clocks are able to provide us with localization with an accuracy of 5–20 m (historically under 100 m). People's dependence on high-performance timing is also demonstrated by telecommunications and defense: each 1% of the time error in a fiber-based telecommunication network degrades the network performance by 1%; similarly, the power consumption and communication range in wireless communication systems also decrease when there is a time error. The saved value can reach as high as $2B if a system has high accuracy ($>$ 200 m) navigation based on, for example, quantum gyroscopic sensors. This poses a new identity for the navigation field, providing the link between the abstract physics performance metrics and the practical performance improvement of a practical quantum-enhanced navigation system. Three cascade case studies with increasing technological readiness show a clear path ahead for quantum-enhanced navigation to transition to real-world applications. The distinct mathematically modeled behavior of a state-of-the-art cold-atom-based navigation system and correlating them to a world-first demonstrate the practical benefit of quantum-enhanced navigation. The navigational context provides a more direct avenue for translating abstract figures of merit to practical performance improvement. At the high end of technological readiness, atomic and superconducting quantum sensors have shown smaller versions of practical quantum-enhanced navigation systems and timing technology. Combining these characteristics, the three case studies are shown in chronological order alongside their position on the technology readiness scale.

Advances in quantum-enhanced technologies have been swift, offering capabilities in sensing, measurement, imaging, and communications. The breadth of potential applications, ranging from the nano scale and beyond to long-distance surveillance, encompasses areas of interest to both the fundamental physics and the practical applications communities. The field's foundation is held up by a variety of back-to-back results and a rapidly expanding series of reviews. Trends in research and commercial development alike are visible through areas of overlap, including variants of nuclear magnetic resonance, atomic magnetometer advances, miniaturization of ride-along magnetic sensors, and demonstrations of quantum-enhanced radiofrequency measurements.

A diversity of trends is visible in the research literature. A number of very recent research articles homogeneously consider entanglement on the micro or nano-scales. Though bottom-up fabrication of large arrays of entangled sensors stands out as a significant emergent challenge, efforts in this direction are the subject of an ongoing project. Notably, two major quantum flagship programs have provided substantial backing, fostering interdisciplinary collaborations that integrate advancements in quantum gradiometry with developments in neuroscience. The jungle of gravitational waves is of particular interest, with new reviews on the potential for applications present in the current journal issues. These applications in quantum physics have lately seen ever-growing appeal, bringing together experts from a variety of widely varied scientific communities.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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