Precisely measuring quantum signals in large spin ensembles

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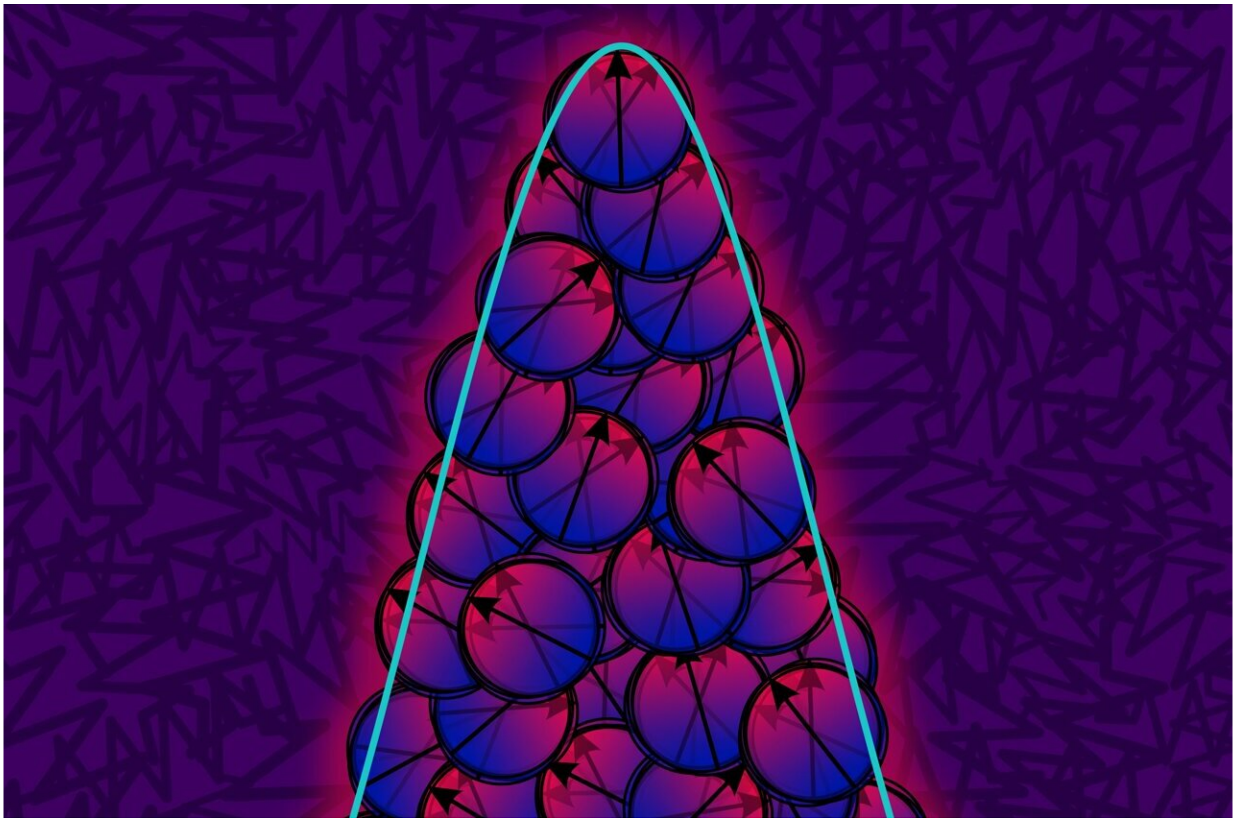

Illustration of a macroscopic ensemble of spins behaving like tiny magnets. Even in such a large system, the team's approach could still detect subtle quantum spin fluctuations (indicated by the varying arrows), recording signals without externally exciting the system. Credit: Kuenstner et al.

Quantum mechanical effects are known to be easily disrupted by disturbances from the surrounding environment, commonly referred to as noise. To minimize these disturbances, physicists often study these effects in small and carefully controlled systems, in which environmental noise can be minimized.

Researchers at Johns Hopkins University set out to study quantum effects in macroscopic spin ensembles, systems comprised of large numbers of spins (spins is the intrinsic angular momentum of elementary particles). Their paper, published in *Nature Physics*, introduces a new approach to directly observe quantum spin fluctuations in macroscopic spin ensembles, precisely monitoring their evolution over time.

"Quantum effects are typically observed and exploited in microscopic systems, where individual qubits can be precisely controlled and measured," Alexander O. Sushkov, senior author of the paper, told Phys.org.

"However, larger qubit ensembles offer significant advantages for sensing and metrology applications. The challenge is that as you scale up quantum systems, classical noise usually overwhelms quantum effects—there's an inherent tension between the sensitivity gained from larger experiments and the ability to maintain quantum behavior."

The recent work by Sushkov and his colleagues draws inspiration from other large-scale quantum measurements performed in recent years, such as the measurements collected by gravitational-wave detectors that rely on large numbers of photons.

Their goal was to introduce a new approach to precisely measure quantum fluctuations in macroscopic systems, which could also help to improve detectors used to search for ultralight axion dark matter.

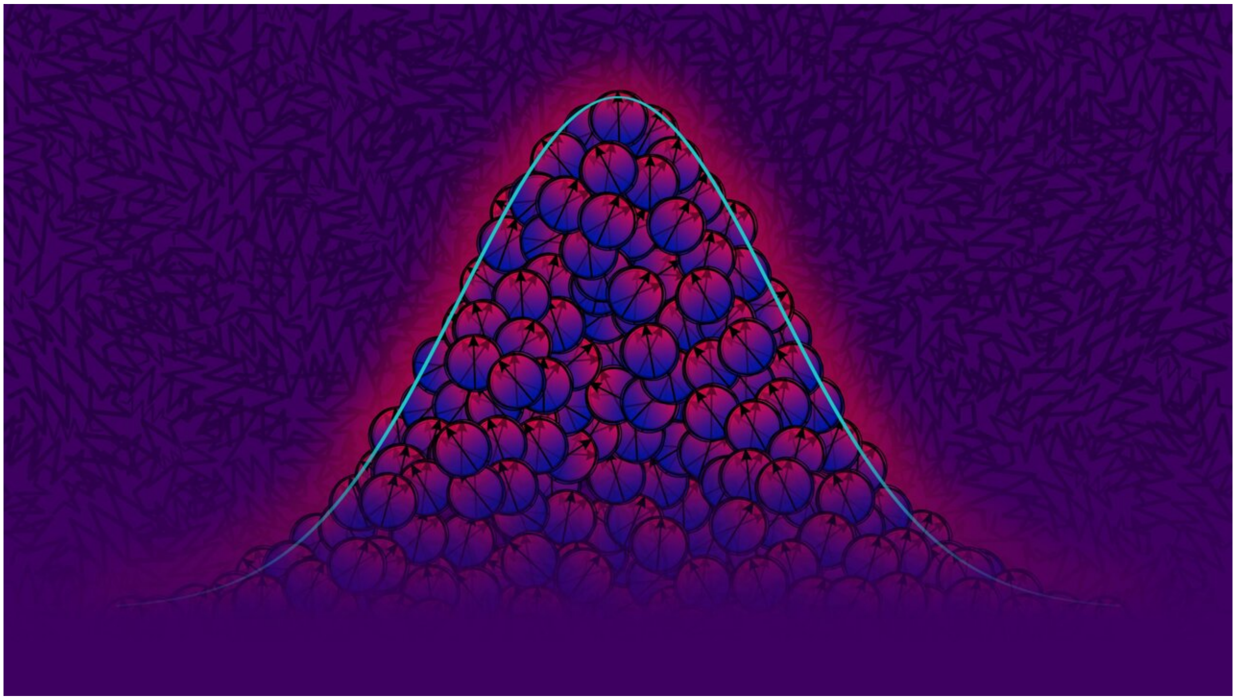

Illustration of a macroscopic ensemble of spins behaving like tiny magnets. Even in such a large system, the team's approach could still detect subtle quantum spin fluctuations (indicated by the varying arrows), recording signals without externally exciting the system. Credit: Kuenstner et al.

Observing quantum spin fluctuations in macroscopic systems

The researchers developed a new quantum measurement system that reaches the quantum limit of detection. This essentially means that the sensitivity of their approach is so high that it approaches the ultimate limit set by the laws of quantum mechanics.

"Our experimental apparatus centers on a superconducting receiver circuit read out by a SQUID (superconducting quantum interference device), an extremely sensitive magnetic field detector," said Sushkov.

"We placed nuclear spin samples (fluorine-19 nuclei in PTFE (Teflon) polymer and hydrogen nuclei in nylon) inside a pickup coil connected to this circuit. The entire system was cooled by a dilution refrigerator to extremely low temperatures, below 1 degree Kelvin."

Many existing approaches for collecting quantum measurements actively stimulate a system and then record the signals arising from this excitation. In contrast, the team's proposed method collects magnetic resonance spectroscopy measurements (i.e., probes the magnetic properties of particles) without the need for any external excitation.

"Instead of applying radio-frequency pulses to the spins (as conventional nuclear magnetic resonance methods do), we used the naturally occurring thermal fluctuations in the circuit as the only driving force," explained Sushkov.

"When we tuned the magnetic field so that the spin resonance frequency matched our circuit's resonance, we observed characteristic changes in the circuit's properties, both frequency shifts and linewidth broadening, caused by the spins' responses.

"By suppressing circuit thermal noise below the level of spin quantum fluctuations through cryogenic cooling, high-quality-factor superconducting circuits, and careful shielding from external electromagnetic noise, we achieved sensitivity at the fundamental quantum limit."

With their approach, Sushkov and his colleagues detected magnetic signals generated by spins in a macroscopic system. Notably, they found that the measurements they recorded were perfectly aligned with quantum mechanical predictions.

"The measured spin angle fluctuations precisely followed the prediction from quantum mechanics," said Sushkov. "They scaled as expected with the number of spins and their polarization, confirming we were detecting genuine quantum spin projection noise."

Advancing spectroscopy and informing dark matter searches

In initial tests, the quantum measurement system introduced by this team of researchers was found to pick up quantum spin fluctuations in a large spin ensemble that would typically be very difficult to detect, as they would be hidden by noise.

Notably, the new approach achieved a precision that is almost four orders of magnitude better than that achieved by other measurement systems introduced in the past.

"Prior experiments had achieved quantum-limited detection in atomic vapor cells containing about 100 billion atoms; we extended this to a solid sample of nearly 5 sextillion (5×10^{21}) spins," said Sushkov. "The smallest measured fluctuation angle was just 9 nanoradians, an extraordinarily precise measurement. This is approximately the angular size of a human being, standing on the moon, when viewed from Earth."

In their paper, Sushkov and his colleagues show that their measurement system could be applied in various fields. Firstly, it could be used to realize non-invasive magnetic resonance spectroscopy, allowing researchers to study materials or physical systems without altering them or disturbing them.

"With our approach, we may be able to study materials without applying any radio-frequency excitation, which is crucial for explosive, correlated, or highly sensitive materials that cannot tolerate conventional

NMR pulses," said Sushkov.

"We could also track spin relaxation with a timescale of over 26 hours, performing non-equilibrium spin-state preparation and measuring subsequent thermalization, without disturbing the system."

An important motivation for the team's recent efforts was to advance detectors used to search for ultralight axion dark matter, hypothetical particles with extremely low masses. The Cosmic Axion Spin Precession Experiment and other similar research efforts are searching for axions using magnetic resonance-based methods that can pick up small spin fluctuations that would hint at the presence of these particles.

The approach developed by the researchers could prove advantageous for running these experiments, due to its high sensitivity and the fact that it can uncover weak signals in large systems. In addition, it could soon inform the development of new technologies that leverage macroscopic spin-squeezed states.

"We have several exciting directions for future research," said Sushkov. "First, our methodology has potential applicability to samples at higher physical temperatures, provided we can maintain circuit performance and quality factors. Scaling up both sample and pickup coil dimensions could extend quantum-limited detection to even larger spin ensembles, though this requires careful management of circuit parameters."

As part of their next studies, Sushkov and his colleagues are now also applying their approach to axion dark matter searches.

"The Cosmic Axion Spin Precession Experiment uses magnetic resonance techniques to search for the interaction between nuclear spins and hypothetical axion particles," added Sushkov.