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Classical-Noise-Free Measurement by High-Order Quantum Correlations

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One main challenge for realistic quantum computing and quantum sensing is to combat noise. Three formal strategies including quantum error correction,[1,2] decoherence-free subspace[3,4] and dynamical decoupling[5] have been developed for suppressing the noise. Quantum systems can lose their coherence when subjected to fluctuations of the local fields from their surrounding environments. Such decoherence phenomena are a fundamental effect in quantum physics and sometimes are referred to as a back-action from the measured system. As one typical dynamical decoupling technique, spin echo originated from magnetic resonance spectroscopy can average out the noise by flipping the target qubit.

During the last decade, nitrogen vacancy center in diamond plays an important role in quantum computing due to its unique long electron spin coherence time. Also, researchers[6,7] experimentally demonstrated an approach to nanoscale magnetic sensing by coherent manipulation of electron spin of nitrogen vacancy center. In an ultra-pure diamond sample, they achieved detection of 3 nT magnetic fields at kilohertz frequencies after 100 s of averaging. This is a spin-echo-based magnetometry with an individual nitrogen vacancy electron spin in a bulk diamond sample.

Generally, there is a back-action from the measured system and this can cause the quantum state to collapse and the system to lose its coherence. If one can measure the dynamics of a quantum object by sequential weak measurements, the back-action can be strongly suppressed. Weak measurements have been demonstrated experimentally with nitrogen vacancy centers[8] and superconducting qubits.[9] Recently, Liu and his collaborators have demonstrated a high-resolution spectroscopy technique by sequential weak measurements[10] on a single ^{13}C nuclear spin. The back-action causes the spin to undergo a quantum dynamics phase transition from coherent trapping to coherent oscillation. The measurement at room temperature with a spectral resolution of 3.8 Hz is achieved. These results enable us to use measurement-correlation schemes for detection of very weakly coupled single spins.

In situ sensing of spin and charge properties under high pressure is important but remains technically challenging. In 2019, Shang *et al.*[11] demonstrated a coherent control and spin dephasing measurements for ensemble nitrogen vacancy centers at 32.8 GPa. With this *in situ* quantum sensor, they have investigated the pressure-induced magnetic phase transition of a micron-size permanent magnet $Nd_2Fe_{14}B$ sample in a diamond anvil cell, with a spatial resolution of 2 μm and sensitivity of 20 $\mu T/Hz^{1/2}$. This scheme could be generalized to measure other parameters such as temperature, pressure and their gradients under extreme conditions.

Interestingly, a recent paper by Wang *et al.*[12] has proposed a new classical-noise-free sensing scheme. Quantum sensing can enhance resolution, precision and sensitivity of detection using quantum properties of sensors. They show that measurement of the quantum correlations of a quantum target indeed allows for sensing schemes that can fully exclude the effects of classical noises. As an example, in the case that the second-order classical correlation of a quantum target could be totally concealed by non-stationary classical noise, the higher-order quantum correlations can single out a quantum target from the classical noise background, regardless of the spectrum, statistics, or intensity of the noise. This scheme suggests new opportunities including sensitivity beyond classical approaches and non-classical correlations as a new approach to quantum many-body physics. Using the example of sensing a single spin, they show that the quantum correlations of a target can be employed to enable classical-noise-free sensing schemes. When the noise has strong non-stationary fluctuations in its correlation spectrum, it would be impossible to detect a target by conventional correlation spectroscopy that measures correlations of classical nature. Quantum correlations can also be measured to fully exclude the effects of the classical noise so that the quantum object is detected. As compared with the conventional noise filtering schemes, the higher-order quantum correlation sensing does not depend on the specific properties of the classical noises.

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