Interference at Decillion Hz Compton Frequency: Enhancing Sensitivity of an Atomic Interferometer to the Heisenberg Limit using Increased Quantum Noise

S M Shahriar1,2, R Fang2, and R Sarkar2

1EECS, Northwestern University, Evanston IL, USA
2Physic and Astronomy, Northwestern University, Evanston IL, USA
Contact Email: shahriar@northwestern.edu

In an atomic interferometer (AI), the signal $S$ can be expressed as a function of the phase difference $\phi$ between the two arms. The measurement sensitivity, $\Lambda$, can be expressed as the inverse of the phase fluctuation (PF): $\Lambda = PF^{-1} = |\partial_{\phi} S/\Delta S|$, where $\partial_{\phi} \equiv \partial/\partial \phi$. Here, $\partial_{\phi} S$ represents the phase gradient of the signal (PGS), and $\Delta S$ represents the standard deviation of the signal (SDS). When all sources of excess noise (EN) are suppressed sufficiently, $\Lambda$ is limited by the quantum projection noise (QPN), and is given by the inverse of the quantum phase fluctuation (QPF): $\Lambda = QPF^{-1} = \sqrt{N}$, with $N$ being the number of atoms interrogated within the measurement time. Using spin-squeezing, it is possible to surpass the SQL, and a key goal in this context is to achieve the Heisenberg Limit (HL), under which $\Lambda = N$, representing an improvement by a factor of $\sqrt{N}$.

To enhance the sensitivity $\Lambda$, one can either increase the PGS or decrease the SDS. In a conventional approach for spin squeezing, one minimizes the variance, and therefore the SDS. For example, using optimal one-axis-twist squeezing (OATS) and two-axis-counter-twist (TACT) squeezing, the SDS can be reduced respectively by a factor of $N^{1/3}$ and $\sqrt{N/2}$, while the PGS remains essentially unchanged, compared to those of a conventional AI. As such, $\Lambda = N^{5/6}$ for the former and $\Lambda = N/\sqrt{2}$ for the latter. Though the TACT squeezing can yield a better sensitivity, it is experimentally more complicated than the OATS.

Recently, it was shown that it is also possible to reach sensitivity at or near the HL using variants of the OATS. For example, the echo squeezing protocol (ESP) can increase the PGS by a factor of $\approx \sqrt{N/2}$, while leaving the SDS unchanged, thus producing $\Lambda \approx N/\sqrt{2}$. Similarly, we recently proposed a Schrödinger Cat atomic interferometer (SCAIN) that makes use of critically tuned OATS, rotation, inverse rotation and unsqueezing, which, in combination with collective state detection (CSD), reduces the SDS by a factor of $\sqrt{N}$, while leaving the PGS unchanged, yielding $\Lambda = N$. In what follows, we will refer to this as the CSD-SCAIN.

In this talk, we will describe a new protocol that is a variant of the CSD-SCAIN protocol, with radically different behavior. It employs the conventional detection (CD) technique by measuring directly the populations of the spin-up or spin-down states of individual atoms. We show that, under this protocol (called CD-SCAIN), the PGS is increased by a factor of $N$, while the SDS is also increased by a factor of $\sqrt{N}$. The net enhancement in the sensitivity is by a factor of $\sqrt{N}$, reaching the HL: $\Lambda = N$. However, because of the increase in noise (i.e., SDS), this is now significantly more robust to EN than all the protocols described above. Specifically, for this protocol, it should be possible to achieve $\Lambda = N/\sqrt{2}$ even when the EN is greater than the QPN for a conventional AI by a factor of $\sqrt{N}$.

The Schrödinger Cat state, which is produced under both CSD-SCAIN and CD-SCAIN protocols, is a superposition of two extremal collective states: one in which all atoms are spin-down, and another in which all atoms are spin-up. When in this maximally entangled state, the ensemble acts as a single particle, with a Compton frequency that is $N$ times larger than that of a single atom. Thus, for an atom interferometric gyroscope using 100 million Rb atoms in each pulse, the interference for both CSD-SCAIN and CD-SCAIN would occur at an ultrahigh Compton frequency of 2 Decillion Hz, with a factor of ten thousand improvement in sensitivity. Interference at such a high frequency is unprecedented, and would represent a revolutionary advance in precision metrology. We will describe how these protocols can also
be realized for other atomic sensors, such as atomic clocks and atomic magnetometers, with the same factor of improvement in sensitivity. Potential applications include accelerometry, gyroscopy and gravity gradiometry, for inertial navigation, geodesy, geophysical studies, and hydrocarbon exploration. Other applications include atomic clocks, magnetometers, measuring fundamental constants, testing general relativity, probing interaction of macroscopic quantum systems with gravity, searches for dark matter, and next generation gravitational wave detection.

Acknowledgements: This work has been supported by NSF under grant DMR-1121262, and AFOSR under grant FA9550-18-01-0401.