

## **Vortex-like light states help create a new kind of qubit for quantum information processing**

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In the 1920s, S. N. Bose and Albert Einstein predicted the Bose-Einstein condensate (BEC), a novel state of matter with quantum mechanical properties in which a collection of particles behaves like a single entity, much like a flock of soldiers marching in unison. BECs were achieved in a laboratory in 1995 and their creators Wolfgang Ketterle, Carl Wiemann and Eric Cornell have received Nobel Prize in physics in 2001. BECs can sustain vortices that are analogous to vortices we see in nature--hurricanes, tornadoes and rotating motion of water rushing down a filled sink. Nevertheless, the laboratory vortices, usually generated in superfluid materials that experience no resistance during their motion, are quantum objects. The quantum nature of these vortices lies in the fact that only discrete (quantum) values of the rotational velocity are allowed for each particle undergoing the rotational motion. The vortices in Bose-Einstein Condensates are macroscopic, as they can be made visible to the eye fairly easily, yet quantum objects.

On another front, for the past 20 years, scientists have been working toward creating a new type of computer that runs on quantum mechanical principles. Our work proposes that the quantum vortices in Bose-Einstein Condensates could be used as the basic entity of quantum information, the qubit. Although still theoretical at this point, a functional quantum computer could have expansive and immediate effects on our society. A quantum computer would be able to factor large numbers instantaneously, which would greatly aid in encoding and decoding secret information. Quantum computers could also serve commercial interests as well. Searches of large databases could be run exponentially faster than is possible today. For example, a phone company interested in calculating the minimal distance to route calls across the country could do so on a quantum computer in a fraction of the time it takes a conventional computer.

Our work proposes to take the quantum nature of the vortices a step further by generating quantum superpositions of two counter-rotating vortex structures in a Bose-Einstein Condensate. The quantum superposition is more than a mere coexistence of two entities involved; they share a special correlation termed as quantum coherence corresponding to a special phase relation between the components. Thus, each particle in the proposed novel state of the Bose-Einstein condensate can coexist in either one of the two counter-rotating vortices. The proposed special vortex states are analogous to the superconducting circuits sustaining two counter-rotating persistent currents and could be useful as quantum-bits (qubits) for future quantum computers. We term this new qubit--a vortex-phase qubit--as it is a macroscopically occupied superposition of two counter-rotating phase structures or quantum vortices. Figure 1 shows a simplified schematic of this new type of qubit.

$$\frac{1}{\sqrt{2}} \left( \left| \begin{array}{c} \text{vortex} \\ \text{rotating clockwise} \end{array} \right\rangle + \left| \begin{array}{c} \text{vortex} \\ \text{rotating counter-clockwise} \end{array} \right\rangle \right)$$

Figure 1. Schematic depiction of the Vortex-Phase Qubit. It consists of two coherently coexisting geometric components. The geometric components are vortices in the Bose-Einstein condensates that are counter-rotating with respect to each other.

It is well known that the vortex structures can exist in light beams as well. These special light beams are usually termed as orbital angular momentum states of light or optical vortices and are fairly easy to generate, manipulate and detect. Each photon, a particle of light, in such a beam carries the same quantum (a discrete value) of angular momentum characteristic of the beam.

Our scheme allows generation of quantum superposition of counter-rotating optical vortices in light beams and through a specially designed coupling scheme we transfer this superposition to an initially non-rotating Bose-Einstein condensate. Thus, we obtain a macroscopic quantum superposition of two counter-rotating vortex states. We also propose a simple detection scheme for such a qubit using the existing detection methods in the BEC community.

Along with opening new opportunities for doing quantum information with long-lived vortex states of Bose-Einstein Condensation this work opens up yet another avenue for fundamental quantum optics as well. Till now there has been no way of coupling the optical vortex states to the quantum degrees of freedom of matter. This work just opens up this possibility with applications ranging from group velocity manipulations, development of quantum memory and new kind of communication protocols via the orbital angular momentum states of light.