Introduction to quantum Cheshire cats

This introductory essay presents the basic idea of quantum Cheshire cats. To begin with, this essay explains the Cheshire cat analogy and its physical meaning. This essay also briefly introduces weak measurements, which are essential when studying quantum Cheshire cats. Further, this text discusses two studies [1, 2] that explore the quantum Cheshire cat behaviour. Finally, this text presents alternative explanations [3, 4] to the results of the two discussed studies.

The Cheshire cat analogy comes from the novel "Alice's Adventures in Wonderland" written by Lewis Carroll. In the novel, the cat can separate its grin from the rest of the body. The analogy links the cat to a particle and the grin to a property of that particle. Thus, a quantum Cheshire cat refers to an effect that seemingly separates a property of a particle from the particle itself. The Cheshire cat effect was named by Aharonov et al. [1].

Studying a quantum Cheshire cat requires special quantum measurements. Weak measurements refer to measurements that affect the state of the system only a little and consequently provide less accurate information. Measurements of quantum systems always have a trade-off – more accurate measurements lead to a larger effect on the state of the system. However, performing numerous weak measurements successively allows a greater accuracy of measurements while not extensively affecting the state of the system.

Quantum Cheshire cats have been proposed theoretically by Aharonov et al. [1] and shown experimentally by Denkmayr et al. [2]. Aharonov et al. propose that a photon and its circular polarization state can be separated from each other. Similarly, Denkmayr et al. show that a neutron and its spin can take different paths in an interferometer. Both studies utilize an interferometer setup that splits a particle beam into two. The split beams take different paths in the interferometer before being merged and interfering with each other. The merged beam is then led to different detectors, which provide information about the paths of the particle and its property. The paths tweak the beams, allowing the detectors to weakly measure which path was taken by the particle and the property.

The authors in [1] use displacements of the photon beam as a pointer of the path of the beam. One path displaces the photons horizontally either to left or right, depending on the circular polarization of the photon. The other path displaces the photons vertically upwards. Thus, the beam path can be measured by determining the beam displacement compared to the centre of the detector. The measurements affect the system strongly if the displacement is greater than the beam diameter. However, the measurements are in the weak measurement region if the displacement is much smaller than the beam diameter.

The results of [1] claim that the polarization can be observed in one path and the photon can be observed in the other path at the same time. The results were concluded from the photon beam being displaced both horizontally and vertically.

The authors in [2] use an absorber to determine the path of the neutron and a magnetic field to determine the path of the spin. They use an absorber with high transmissivity and a weak magnetic field to obtain weak measurements. The authors find that the absorber is only effective on one path and the magnetic field is only effective on the other path. Thus, they conclude that the neutrons and their spins seem to be separated from each other in this setup.

However, the conclusions of [1] and [2] have been challenged [3], [4]. Corrêa et al. [3] deny the need for a statement that a particle and its property can be separated. Instead, the authors claim that the quantum Cheshire cat effect “can be understood as simple quantum interference”. Alternatively, Saeed et al. [4] propose that the polarization of a photon becomes temporarily “dormant” instead of disembodying from the photon in the interferometer.

The quantum Cheshire cat is truly a mind-bending effect. It displays a fitting example of the classically paradoxical nature of many quantum phenomena. As described, different interpretations of the effect have been studied, and the existence of a quantum Cheshire cat remains a controversial topic for ongoing research.

[1] Y. Aharonov, S. Popescu, D. Rohrlich, and P. Skrzypczyk, “Quantum cheshire cats,” *New Journal of Physics*, vol. 15, no. 11, p. 113015, Nov. 2013, doi: 10.1088/1367-2630/15/11/113015.

[2] T. Denkmayr *et al.*, “Observation of a quantum cheshire Cat in a matter-wave interferometer experiment,” *Nature Communications*, vol. 5, no. 1, pp. 1–7, Jul. 2014, doi: 10.1038/ncomms5492.

[3] R. Corrêa, M. F. Santos, C. H. Monken, and P. L. Saldanha, “‘Quantum Cheshire Cat’ as simple quantum interference,” *New Journal of Physics*, vol. 17, no. 5, p. 053042, May 2015, doi: 10.1088/1367-2630/17/5/053042.

[4] M. H. Saeed, M. Imran, H. Tariq, Rameez-ul-Islam, and M. Ikram, “Quantum Cheshire cat: a physically realistic interpretation by invoking entangled correlations,” *Journal of the Optical Society of America B*, vol. 38, no. 4, p. 1147, Apr. 2021, doi: 10.1364/josab.414000.