Error-disturbance uncertainty relations and the quantum Cheshire Cat studied in neutron optical experiments

S. Sponar, G. Sulyok, T. Denkmayr, H. Geppert, H. Lemmel, and Y. Hasegawa

Atominstitut - Vienna University of Technology, Stadionallee 2, 1020 Vienna, Austria

e-mail: sponar@ati.ac.at

Abstract

Neutron interferometry [1], where an interference effect of matter-waves passing through a perfect silicon-crystal interferometer is observed, and neutron polarimetry (also referred to as spin-interferometry) have established as a powerful tool for investigation of fundamental quantum mechanical concepts using massive particles. The former technique enabled several textbook experiments, such as demonstrations of 4π spinor symmetry of spin - $1/2$ particles, spin superposition, gravitationally induced phase and topological phase effect, as well as studies of characteristics of intra-partite entanglement, i.e., entanglements between different degrees of freedom. The latter was utilized for demonstration of anti-commuting properties of Pauli spin matrices, topological phase measurements, and tests of alternative theories of quantum mechanics [2].

Recently, Heisenberg's error-disturbance uncertainty relation has been studied in neutronic and also photonic quantum systems. In 2003 Ozawa introduced a generalized universally valid ererror-disturbance uncertainty relation (EDR) [3]. In my talk, I am going to give an overview of our neutron optical approaches for investigation of error-disturbance uncertainty relation via a successive measurement of incompatible neutron spin observables (e.g. $\hat{A} = \hat{\sigma}_x$ and $\hat{B} = \hat{\sigma}_y$) [4]. The disturbance $\eta(\hat{B})$ on the observable $\hat{B}$ is induced by the measurement of the observable $\hat{A}$ with error $\epsilon(\hat{A})$. Though universally valid Ozawa's relations is not optimal. Recently, Branciard [5] has derived a tight EDR, describing the optimal trade-off relation between error $\epsilon(\hat{A})$ and disturbance $\eta(\hat{B})$. Our experimental results clearly demonstrat the validity of Ozawa's and Branciard's EDRs and that the original Heisenberg EDR is violated throughout a wide range of experimental parameters.

In addition, a new counter-intuitive phenomenon, the so-called quantum Cheshire Cat [6], is demonstrated in an neutron interferometric experiment: If a quantum system is subject to a certain pre- and postselection, it can behave as if a particle and its property are spatially separated. In our experiment weak values of the neutron's path and spin are determined, suggesting that for the successfully postselected ensemble the neutrons go through one beam path of the interferometer, while their spin travels along the other [7].

Keywords: Neutron, Spin, Interferometry

References

[1] H. Rauch and S. A. Werner, *Neutron Interferometry* (Clarendon, Oxford, 2000).

[2] J. Klepp, S. Sponar, and Y. Hasegawa, Prog. Theor. Exp. Phys., **2014**, 082A01.

[3] M. Ozawa, Phys. Rev. A **67**, 042105 (2003).

[4] J. Erhart, S. Sponar, G. Sulyok, G. Badurek, M. Ozawa, and Y. Hasegawa, Nat. Phys. **8**, 185 (2012).

[5] C. Branciard, Proc. Natl. Acad. Sci. USA **110**, 6742 (2013).

[6] Y. Aharonov, *et al.*, New J. Phys. **15**, 113015 (2013).

[7] T. Denkmayr, H. Geppert, S. Sponar, H. Lemmel, A. Matzkin, J. Tollaksen, and Y. Hasegawa, Nat. Commun. **5**, 4492 (2014).