Testing Fundamental Axioms of Quantum Mechanics *Via* X-Ray Quantum Optics

D Lentrodt[1], M O Pleinert[2], E I Saruhan[2], R Röhlsberger[3,4], and J von Zanthier[2]

[1] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
[2] *Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany. Contact Phone: +4991318527603*
[3] *no department, DESY, Hamburg, Germany*
[4] *Institute of Optics and Quantum Electronics, Friedrich-Schiller-Universität Jena, Jena, Germany*
Contact Email: joachim.vonzanthier@fau.de

Fundamental axioms of quantum mechanics like Born's rule or the number system of the Hilbert space have been called into question since the invention of the theory [1,2]. Born's rule relates detection probabilities to the modulus square of the wave function [3]. Consequently, indistinguishable quantum paths contributing to the same wave function give rise to interferences. In 1994, R D Sorkin proposed an experimental setup to test deviations from Born's rule in a quantitative manner [4]. The scheme, based on quantum path interferences, has been applied in various domains over the last 15 years [5-8], limiting deviations from the so-called Sorkin parameter down to the level of $10^{-}3$ [8]. A further building block of quantum theory is the use of complex valued wave functions. Yet, other quantum-mechanical formulations using a Hilbert space based on real numbers or hyper-complex numbers are technically possible. Renou *et al.* suggested recently a Bell-like experiment to show the inadequacy of a real-valued theory [9]. This has been experimentally verified soon afterwards with photons [10] and superconducting qubits [11], even though the test is still under debate [12,13]. Attention turned early on also to higher-dimensional formulations of quantum mechanics. In 1979, A Peres proposed a test to differentiate between a complex and hyper-complex quantum theory [14]. Recently, measurements of the Peres test have been realized in the optical [15] and microwave regime [16], however not yet able to rule out hyper-complex theories. In most of the experiments performed so far, the precision is limited due to the observation of spatial interferences where measurements are affected by large systematic effects. Here, we propose to implement the Sorkin and the Peres test exploiting a multi-path interferometer in the time domain. This is done by using interferences generated by X-ray photons scattered from different targets or transitions of Mössbauer nuclei. In the talk, we will outline the scheme and discuss possible advantages and limitations.

References

[1] E Schrödinger, Ann. Phys. **79**, 361 (1926)

[2] G Birkhoff and J V Neumann, Ann. Math. **37**, 823 (1936)

[3] M Born, Z. Phys. **37**, 863 (1926)

[4] R D Sorkin, Mod. Phys. Lett. A **9**, 3119 (1994)

[5] U Sinha, C Couteau, T Jennewein, R Laflamme and G Weihs, Science **329**, 418 (2010)

[6] T Kauten, R Keil, T Kaufmann, B Pressl, C Brukner and G Weihs, New J. Phys. **19**, 033017 (2017)

[7] J P Cotter, C Brand, C Knobloch, Y Lilach, O Cheshnovsky and M Arndt, Sci. Adv. **3**, e1602478 (2017)

[8] T Vogl, H Knopf, M Weissflog, P K Lamand F Eilenberger, Phys. Rev. Res. **3**, 013296 (2021)

[9] M-O Renou, D Trillo, M Weilenmann, T P Le, A Tavakoli, Ns Gisin, A Acín and M Navascués, Nature **600**, 625 (2021)

[10] Z-D Li, Y-L Mao, M Weilenmann *et al.*, Phys. Rev. Lett. **128**, 040402 (2022)

[11] Mg-C Chen, C Wang, F-M Liu, *et al.*, Phys. Rev. Lett. **128**, 040403 (2022)

[12] P Barrios Hita, A Trushechkin, H Kampermann, M Epping and D Bruß, arXiv:2503.17307 (2025)

[13] T Hoffreumon and M P Woods, arXiv:2504.02808 (2025)

[14] A Peres, Phys. Rev. Lett. **42**, 683 (1979)

[15] S Gstir, E Chan, T Eichelkraut, A Szameit, R Keil and G Weihs, New J. Phys. **23**, 093038 (2021)

[16] S Sadana, L Maccone and U Sinha, Phys. Rev. Res. **4**, L022001 (2022)