TUE 7: Entanglement and Complexity: Contributed Session to Symposium I

Time: Tuesday 14:15–15:45 Location: ZHG008

TUE 7.1 Tue 14:15 ZHG008

Experimental Demonstration of Electron-Photon Entanglement — •Sergei Bogdanov[1,2], Alexander Preimesberger[1,2], Isobel C. Bicket[1,2], Phila Rembold[1], and Philipp Haslinger[1,2] — [1]Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Vienna, Austria — [2]University Service Centre for Transmission Electron Microscopy (USTEM), TU Wien, Vienna, Austria

Quantum entanglement, a fundamental resource for quantum technologies, describes correlations between particles that cannot be explained by classical physics. While transmission electron microscopes (TEMs) are well-established tools with exceptional spatial resolution, their potential for exploring quantum correlations remains largely underexplored. In this study, we demonstrate entanglement between electrons and photons generated via cathodoluminescence inside a TEM. To produce correlated electron-photon pairs we use a TEM working at 200 keV to illuminate a 50 nm silicon membrane. Inelastic scattering of electrons may lead to the emission of cathodoluminescent coherent photons. Due to energy and momentum conservation, transmitted electrons and emitted photons are correlated in position and momentum. A custom-made parabolic mirror directs the photons out of the TEM to an optical detection system. To perform coincidence measurements, an absorptive grating mask is used as the object for ghost image formation. We reconstruct near- and far-field "ghost" images of the periodic masks and show a violation of the classical uncertainty bound. Hence, we demonstrate position-momentum entanglement of electron-photon pairs, bridging quantum optics and electron microscopy.

TUE 7.2 Tue 14:30 ZHG008

Experimental measurement and a physical interpretation of quantum shadow enumerators — •Daniel Miller[1,7], Kyano Levi[1], Lukas Postler[2], Alex Steiner[2], Lennart Bittel[1], Gregory A.L. White[1], Yifan Tang[1], Eric J. Kuehnke[1], Antonio A. Mele[1], Sumeet Khatri[1,3,4], Lorenzo Leone[1], Jose Carrasco[1], Christian D. Marciniak[2], Ivan Pogorelov[2], Milena Guevara-Bertsch[2], Robert Freund[2], Rainer Blatt[2,5], Philipp Schindler[2], Thomas Monz[2,6], Martin Ringbauer[2], and Jens Eisert[1] — [1]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [2]Universität Innsbruck, Institut für Experimental- physik, Technikerstrasse 25, 6020 Innsbruck, Austria — [3]Department of Computer Science, Virginia Tech, Blacksburg, Virginia 24061, USA — [4]Virginia Tech Center for Quantum Information Science and Engineering, Blacksburg, Virginia 24061, USA — [5]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, 6020 Innsbruck, Austria — [6]Alpine Quantum Technologies GmbH, 6020 Innsbruck, Austria — [7]Institute for Theoretical Nanoelectronics (PGI-2), Forschungszentrum Jülich, 52428 Jülich, Germany

We show that Rains' shadow enumerators are the same as triplet probabilities in two-copy Bell sampling. We measure them in experiments.

TUE 7.3 Tue 14:45 ZHG008

Why Quantum Mechanics needs 'Hidden' Variables — •Wolfgang Paul — Martin-Luther-Universität Halle-Wittenberg, Institut für Physik, 06099 Halle

One early culmination point of the discussion on whether the Hilbert space description of quantum mechanics can be considered complete or not are the famous breakfast and dinner conversations between Bohr and Einstein during the 5th Solvay Conference 1927. While Einstein thought that it should be augmented by ontological objects (hidden variables) Bohr insisted that this can not be done.

Bohr was well aware that he declared the death of a good part at the heart of physics as it had been established for the preceding 300 years: his position denied quantum physics the ability to model the measurement process and reduced it to the accounting of measurement results.

Based on Nelson's stochastic mechanics approach [1], one can formulate a model of particles with spin as possessing position and orientation degrees of freedom and describe the measurement process in the Stern Gerlach experiment as well as the Einstein-Podolski-Rosen-Bohm thought experiment [2]. The outcome statistics agree with the Hilbert space quantum mechanical predictions, even reproducing the violation of Bell's inequalities, but in addition the complete measurement process can be followed in a time-resolved manner, so there is no measurement problem any more.

[1] E. Nelson, Phys. Rev. **150**, 1079 (1966)

[2] M. Beyer, W. Paul, Found. Phys. **54**, 20 (2024)

TUE 7.4 Tue 15:00 ZHG008

The dynamic meaning of the Lorentz transforms of mass and time — •Grit Kalies[1] and Duong D. Do[2] — [1]HTW University of Applied Sciences, Dresden, Germany — [2]The University of Queensland, Brisbane, Australia

We describe acceleration as a complex process in which a particle or body changes several of its properties, not just its momentum. Consequently, during acceleration, several forms of energy of an object change, not just its motion energy, which means that its so-called rest energy becomes Lorentz-variant. This insight is made possible by representing particles as physical waves and by applying thermodynamic principles to individual quantum objects, whose property changes are described by several simultaneously occurring forms of quantum work. The results form the basis for the emerging field of quantum-process thermodynamics.

TUE 7.5 Tue 15:15 ZHG008

Role of Nonstabilizerness in Quantum Optimization — •Chiara Capecci[1,2], Gopal Chandra Santra[1,2], Alberto Bottarelli[1,2], Emanuele Tirrito[3], and Philipp Hauke[1,2] — [1]Pitaevskii BEC Center, CNR-INO and Department of Physics, University of Trento, Via Sommarive 14, I-38123 Trento, Italy — [2]INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Via Sommarive 14, I-38123 Trento, Italy — [3]The Abdus Salam International Centre for Theoretical Physics (ICTP), Strada Costiera 11, 34151 Trieste, Italy

Quantum optimization is a promising method for tackling complicated classical problems using quantum devices. However, the extent to which these algorithms exploit genuine quantum resources and the role of these resources remain open questions. We investigate the resource requirements of the Quantum Approximate Optimization Algorithm (QAOA) using nonstabilizerness measurements. We demonstrate that nonstabilizerness increases with circuit depth, reaches a maximum, then decreases approaching the solution state — creating a barrier that limits algorithm's capability for shallow circuits. We find that curves for different depths collapse under simple rescaling and uncover a relationship between final nonstabilizerness and success probability. A similar barrier is found in quantum annealing. These results clarify how quantum resources influence quantum optimization.

TUE 7.6 Tue 15:30 ZHG008

Rethinking Quantization: Toward a Local, Realistic Interpretation — •Falk Rühl — D52159 Roetgen, Auf der Alm 14

More than a century after the birth of quantum theory, its formalism has matured, but its interpretation remains entangled with the early 20th-century notion of 'early quantization'. In this conventional view, central to the Copenhagen interpretation, proposed by A. Einstein and N. Bohr, quanta are treated as discrete property carrying objects, generated at sources and transmitted without loss to distant targets.

In this talk, I will present an alternative framework: 'late quantization'. Here, quantum phenomena arise not from the emission, transfer, and absorption of discrete quanta, but from the interaction of radiation from all possible sources, with continuously evolving states of the targets themselves. This shift allows for a local and realistic interpretation of quantum processes, dispensing with the need for non-locality, wave-function collapse, or quantum jumps.

A key feature of this approach is that efficient detection of sources only occurs, when the source radiation drives closed cycles in the target's state space. This makes only a small subset of the continuously evolving 'beable' states of sources 'observable' states.

This new interpretation not only provides conceptual clarity but also eliminates longstanding quantum puzzles within a fully local and deterministic framework.