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THEORETISCH-PHYSIKALISCHEN KOLLOQUIUM

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Experiments to Probe Quantum Linearity at the Interface to Gravity & Complexity

Donnerstag, 20.12.2018
11:00 Uhr
N24/252

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Quantum physics is the uncontested and best-confirmed theory of nature, and yet a number of essential questions still need to be solved:

Why do we find a unitary and linear evolution in quantum mechanics and its relativistic extensions but not in the macroscopic world we live in? What defines the cut between coherent superpositions of quantum states and the classical world view where irreversible measurements pick one of potentially many mutually exclusive possibilities? How can measurement play the trick if it is a quantum interaction itself? What is the role of complexity or gravity in the quantum-to-classical transition?

These questions have been guiding our research in prototypical test of the quantum nature of matter, which can be regarded as modern extensions of the double slit experiment with massive particles.

Starting from the demonstration of diffraction of hot fullerenes at nanomechanical[1] and optical[2] nanostructures, we have generalized this experiment to full-fledged matter-wave interferometry with mesoscopic objects in different experimental configurations with nanomechanical [3, 4], phase gratings[5] and purely optical photo-depletion gratings[6].

We were able to demonstrate the de Broglie wave nature of complex many body systems such as molecular clusters[7], macromolecules[8] and biomolecules[9], even with molecules more massive than 10’000 amu, composed of more than 800 atoms[10]. In all these experiments, quantum mechanics was well confirmed and always clearly distinct from a classical world view.

We show that one can measure internal particle properties, such as structural conformations[11], electronic[12], magnetic and optical[13] properties, *while* molecules are being quantum delocalized and even at internal microcanonical temperatures of up to 1000 K. The experiments illustrate that quantum superposition states of momentum and position can be realized and visualized even for complex bodies that we would commonly associate with the classical world, for instance when we eat them[9].

If all this can be done, what prevents the appearance of Schrödinger cat states in our everyday lives? Is there a limit in mass, or complexity? This is a valid experimental question that deserves attention, independent of any theory. Models provide additional motivation:

Decoherence theory[14, 15] offers a perfectly valid explanation for the absence of quantum phenomena in a world that is still highly quantum and entangled by unavoidable interactions between a subsystem and its environment. However, decoherence theory does not address the philosophical question whether quantum superpositions may break under any circumstances at any time.

Testing for objective wave function collapse in real space, either spontaneously[16, 17] or mediated by gravity[18, 19] has been the goal of models[20] that extend the Schrödinger equation by non-linear. While many versions of such models have already been constrained by non-quantum experiments[21], genuine quantum experiments in the regime of 10^7-10^{12} amu appear important and necessary to test these models, definitely. The future realization of quantum superposition states in this mass range could also shed light on models that combined quantum mechanics and gravity theory, such as the Schrödinger Newton equation[22].

Even before this is realized, various additional effects of gravity do enter quantum interference experiments: gravitational free fall constrains the coherent evolution and observation time for un-trapped quantum systems. Gravity can also imprint large phase shifts on matter-waves whose partial components probe different heights in the Earth's gravitational field. It has been considered whether high-mass interference might be sensitive to gravitational waves[23] or dark matter[24] or unconventional tests of the weak equivalence principle[25]. Some of these phenomena will be briefly revisited to point to the state of the art and future research directions in the lab, in drop towers and on satellites[26].

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