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Fundamental Frontiers of Quantum Science and Technology

Markus Arndt[a,*], Angelo Bassi[b], Domenico Giulini[c], Antoine Heidmann[d], Jean-Michel Raimond[e]

[a] Vienna Center for Quantum Science and Technology, University of Vienna, Faculty of Physics, Boltzmanngasse 5, A-1090 Vienna, Austria
[b] Department of Physics, University of Trieste, Strada Costiera, 11-34151 Miramare-Trieste, Italy
[c] Institute for Theoretical Physics, University of Hannover, Appelstrasse 2, D-30167 Hannover, Germany & Center of Applied Space Technology and Microgravity, Am Fallturm 1, D-28359 Bremen, Germany
[d] Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Case 74, 4 place Jussieu, F-75252 Paris, France
[e] Laboratoire Kastler Brossel, Ecole Normale Supérieure, CNRS et Université Pierre et Marie Curie, 24 rue Lhomond, F-75005 Paris, France

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Abstract

We discuss recent studies on the foundations of quantum physics with photonic, atomic, molecular and micromechanical systems as well as theoretical treatments of the interface between quantum physics and classical observations. Investigations of the type presented here elucidate important boundary conditions for quantum mechanics and help assessing their relevance for future quantum technologies.

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1. The scientific basis of modern quantum technologies

Over the last five decades an exponential increase in computational power has been consistently maintained and it will probably last for another decade or two before the computational elements become small enough for quantum phenomena to become dominant.

Meanwhile, the high degree of control and theoretical understanding that could be obtained on elementary quantum systems has stimulated research in complex quantum phenomena for future information processing technologies, as well. Rapid developments in the field have led to new quantum communication and computation protocols, quantum key distribution, quantum repeaters and teleportation, to quantum logic gates, quantum memories and more. Most of these new technologies exploit the highly non-classical features of quantum physics, in particular the quantum superposition of classically mutually exclusive states and the inseparable quantum correlation of two or more systems, i.e. entanglement. While quantum computing is still in the status of advanced basic research, many *quantum sensors* exploit the superposition principle already commercially, for instance in atomic clocks, nuclear magnetic resonance imaging or quantum interference metrology. Quantum-enhanced devices are already now an important part of modern technology and their relevance will significantly grow in the future.

The basis of quantum physics has, however, remained a matter of debate since its first formulation. The probably most famous illustration of the conceptual challenge in extrapolating quantum physics to our macroscopic world

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* Corresponding author. Tel.: +43-1-4277-51210; fax: +43-1-4277-9512.
E-mail address: markus.arndt@univie.ac.at (M. Arndt).

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originates in a thought experiment by Erwin Schrödinger [1] who speculated about a mechanism that would quantum correlate the decay of a radioactive atom with a mechanism to kill a cat. The superposition of atomic eigenstates would cause the cat to be both dead and alive at the same time.

Such macroscopic quantum states have never been observed and they would be regarded as absurd. Schrödinger's proposal raised, however, an important question for all future quantum technologies with economic relevance: what are the practical or fundamental limits for mastering quantum superpositions in truly complex objects? One may even ask whether quantum physics will require some generalizations to render it compatible with general relativity or our everyday (classical) experience. We here discuss a set of experiments and considerations which focus on this quantum-classical interface.

2. Cavity quantum electrodynamics

Historically, quantum physics was triggered by research on the nature of thermal light. Modern experimental cavity quantum electrodynamics (CQED) now studies the quantized electric field at the level of single photons up to complex non-classical field states. This can for instance be done by storing microwaves in resonators of unprecedented quality ($Q \geq 4 \times 10^{10}$) and by coupling them to atoms in highly excited circular Rydberg states which exhibit long life times and enormous polarizabilities [2,3]. This unique experimental combination enables the non-destructive detection of individual photons as well as the manipulation of both atoms and photons at a level of control that is only limited by the laws of quantum nature.

Classical light fields are unavoidably associated with an uncertainty in the number of photons and the phase. CQED permits to generate *Fock states*, i.e. states with a well-defined photon number and many interesting applications in quantum information processing, or *Schrödinger cat states,* which are equally non-classical states of light composed of dozens of microwave quanta teaming up in a superposition of distinct field phases.

The perfect experimental control also provides a tool for studying decoherence, for answering the question how a pure quantum system may gradually lose its peculiar superposition property and become apparently classical, i.e. non-quantum, again. Decoherence is probably the most important obstacle to many-body quantum information processing. CQED decoherence metrology may quantify some of the critical processes. CQED also opens the way for establishing active feedback schemes for stabilizing useful but sensitive quantum states, for extended periods of time. Experiments that were conceived to explore the foundations of physics have thus become important for understanding the elements of quantum information and sensing devices. Modern cavity quantum electrodynamics covers a wide range of systems and technologies including atoms, molecules or quantum dots in microwave resonators, high finesse optical cavities or superconducting strip-line resonators.

3. Molecular quantum nanophysics

Quantum interference experiments with macromolecules, large clusters or nanocrystals are currently motivated by three major questions: On the one hand they allow us to explore the validity of the quantum superposition principle in a mass and complexity domain that has been inaccessible hitherto. Macromolecules are massive and complex, with internal temperatures even exceeding that of many classical bodies in real life. And yet, their center-of-mass motion can still be prepared in a quantum state. Recent experiments verified the quantum wave nature of organic molecules with up to 430 atoms and masses up to 6910 amu [4]. Forthcoming experiments aim at the mass range between $10^5 \ldots 10^7$ amu. They relate to the question whether the absence of quantum phenomena in our daily life is rather of technological or fundamental nature. A proper answer to this question will also guide the way to improved quantum technologies in complex systems. Quantitative experiments allowed already to monitor decoherence, i.e. the gradual transition between quantum and classical appearances as caused by collisions with particles in the environment or the emission of thermal photons. Experiments in the high-mass regime may eventually even test proposals for modifications of quantum mechanics.

Secondly, matter waves interferometers are precise quantum-enhanced sensors for nanoparticle properties, which are often computationally hardly accessible and yet relevant for instance for chemistry or biology: Molecules exposed to external fields in a matter wave interferometer experience an interference fringes shift which contains useful information about their polarizability, dipole moment, vibrational dynamics, molecular spectra, magnetic properties or conformational compositions [4].

Finally, matter interferometers may represent a versatile non-contact printing method for creating surface-deposited molecular nanopatterns [5]. Future extensions shall allow to cover mm^2 areas with molecules separated on average by less than 50 nm.

4. Quantum optomechanics

Mechanical oscillators have always been used as model systems to illustrate the laws of quantum physics. Recent efforts worldwide have focused on actually realizing quantum ‘mechanics’ in the literal sense by shrinking the size, by isolating the mass and by lowering the temperature of the mechanical systems. Enormous progress has been made over the last decade in cleverly using light pressure to cool and control mechanical resonators [6,7], with sizes ranging from a few hundred nanometers up to the size of mirrors in gravitational-wave detectors.

A key goal is to obtain maximal control and to generate non-classical mechanical states in mesoscopic systems. The strong coupling between light and an oscillator combines many questions of CQED with advanced concepts of laser cooling, quantum information processing and quantum sensing. This way, optical methods now enable cooling to temperatures significantly lower than typically achieved using cryogenic pre-cooling.

Future experiments and technologies will exploit the quantum entanglement of micromechanical systems with light, atoms or molecules. A macroscopic superposition of two oscillator states would also allow for probing new models of gravitationally induced wave collapse models. The ultrasensitive readout of mechanical displacements that can be achieved nowadays, open also the ways to position sensors that are interesting for diverse applications ranging from gravity wave measurements down to quantum microbalances in advanced mass spectrometry. Similar to other solid-state techniques mechanical systems appear to be compatible with future high-density chip integration.

5. On the role of gravity in quantum superposition experiments

Among the key questions of modern physics the unresolved connection between quantum physics and gravity is often cited as the most pressing one. It is therefore of interest to study genuine quantum systems in the context of gravitational experiments. Current proposals range from testing the universality of free fall, tests of Lorentz invariance or the universality of atomic clock rates up to experiments with quantum gases or molecular matter waves in microgravity and in tests of the equivalence principle.

One may also ask in reverse, how space-time probes or influences the evolution of quantum waves and whether, ultimately, self-gravity may impose a limit on the maximal mass or separation in matter-wave based quantum sensors. One possible approach to that is to solve the Schrödinger-Newton equation, i.e. a formalism that combines a classical space-time model with a mass distribution determined by the quantum wave function.

Recent numerical simulations indicate that gravity could cause a collapse, i.e. a spatial contraction, of an initially delocalized quantum wave function and thus set a fundamental limit to certain types of quantum sensors, too. They predict a contraction starting at 10^4 s for a mass of $10^9 \ldots 10^{10}$ amu initially delocalized over a ∼500 nm [8]. This still does not impose any limit on quantum technologies of the next decade. But the model supports the view that non-trivial effects could occur when exploiting high-mass quantum superpositions at the micrometer scale. This still assumes classical gravity. If quantum gravity were relevant at a mesoscopic scale, one would also have to assess the influence of space-time fluctuations on the quantum superposition in matter wave interferometry or long distance quantum communication.

6. Non-linear extensions of quantum mechanics?

The rules of quantum physics are known to perfectly fit the microscopic world of atoms or molecules but our daily experience on the human scale leaves room for questioning the universality of the quantum superposition principle. This freedom allows for the possibility of modifying quantum theory towards the macroscopic scale, in order to solve paradoxes as that exemplified by Schrödinger’s cat argument. This possibility might have concrete consequences also for quantum sensors and quantum information devices.

Already two decades ago, first proposals described the possibility of a collapse of the wave function as an objective physical mechanism. Throughout the years, this idea has been refined [9,10] and has produced phenomenological models that extend established non-relativistic quantum physics by adding non-linear and stochastic terms to the dynamics. These new terms induce the spontaneous collapse of the wave function with a rate, which scales with the size of the system. Collapse models are useful, as they provide quantitative information on the scale at which quantum mechanics might possibly break down and new physics could emerge, if future experiments find a violation of the superposition principle.

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