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How to extend quantum experiments

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This paper is dedicated to Prof. Paolo Tombesi on the occasion of his 70th birthday.

Modern experimental developments allow to address the fundamental challenges of quantum physics on new, macroscopic scales. How far can such experiments be pushed with current technology? We discuss three specific examples, long-distance photonic entanglement, matter wave interferometry and superposition states of mechanical resonators, and discuss possible extensions to these experiments. It turns out that there is "plenty of room at the top" for macroscopic quantum experiments, even with presently available technology.

1 Introduction

The counter-intuitive properties of quantum mechanics for individual systems have probably first been publicly discussed in Albert Einstein's famous 1909 presentation in Salzburg to the Annual Meeting of the 'Deutsche Gesellschaft der Ärzte und Naturforscher' [1]. There, Einstein pointed to the conceptual challenges related to the idea of light quanta if interference also persists on the level of individual photons. At Einstein's time this fact was not yet experimentally confirmed, but today, interference of single photons, or more generally single particles is standard practice in many laboratories world-wide. In all these experiments, the predictions of quantum theory have been perfectly confirmed and even extended to multi-particle interference and entanglement. These results require a drastic revision of our intuitive world-view. We argue that extending quantum experiments into hitherto untested parameter regimes will help to sharpen our view on this question and will shed new light on our understanding of quantum theory – for example by closing remaining loopholes in existing Bell experiments, by providing even more drastic examples of counter-intuitive quantum phenomena in the spirit of Schrödinger's cat [2] or by establishing new incompatibility theorems in the spirit of Bell's inequalities that are related to macroscopic properties [3]. In the following we will discuss prospects for such extensions for quantum experiments with entangled photons, with matter waves and with massive mechanical resonators.

2 Extending experiments with entangled photons

The first quantum experiments involving truly single particles have been performed with photons (for a review see for example [4] and references therein). A common method to ensure the presence of single

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photons in an apparatus exploits the emission of photon pairs as are provided by atomic decay cascades [5, 6], or optical parametric down-conversion [7]. In these experiments, one photon in the pair is used to indicate the presence of the other photon, which may then be subject to an interference experiment. The first investigations of that kind were performed by Clauser, who sent each particle through a separate beam splitter [5], and by Aspect and Grangier, who submitted one of the two photons to interference while the other one was serving as a trigger to indicate the presence of the single second photon [6].

Quantum mechanics also allows the superposition of two or more individual particles or properties, i.e. entanglement, and many experiments have confirmed the predictions of quantum mechanics in great detail. In particular, entanglement has always been identified as a key to the understanding and interpretation of quantum physics. It is therefore important to devise experiments which help us to confirm established assumptions and to close the loopholes that may still exist for a local realistic, non-quantum, world-view. Here, we will briefly discuss the particular question how to rule out the hypothetical possibility that separate events in such experiments are still determined by some earlier common causes.

In order to eliminate any unknown communication between two measurement apparatuses [8, 9] or between the source (emission) and the detector [10], experiments have been performed with space-like separated random number generators [9, 10]. In these investigations care was taken to exploit the best possible random number sequence, which relies on the well-tested stochastic nature of the photon partition noise at an optical beam splitter [11]. And yet we still have to consider the possibility that even the two remotely located random number generators might be influenced by some common cause. Certainly, the confirmation of such a hypothesis would be a major upheaval of the quantum view of the world, but this is exactly what is at stake in such experimental tests.

There are two possibilities how to address this question. The first one is to involve human decisions, rather than a physical device, to choose which measurement to perform on the two photons. Evidently, the reasonableness of such an experiment depends on the nature of decision processes and the human mind. The proposed experiment is meaningful if we assume that humans have free will in some reasonable sense of the word. We point out that this assumption is a matter of intense debate in current brain research, but we suggest that, strictly speaking, the question is not settled yet. We may consider an experiment with humans making decisions about the measurements on entangled photon pairs, either like in a test of Bell's inequality or in an experiment where one photon serves as the indicator for the presence of another photon traversing an interferometer. A measurement on the first photon then decides whether the second photon passes a well-defined path , i.e. does not show interference fringes, or whether the path of the second photon is undetermined and interference fringes occur. Given the fact that the human decision process takes of the order of tenths of seconds, it is advisable to separate the two experimentalists by distances of the order of at least half a light second, i.e. 150.000 km. Such experiments could be performed between Earth and Moon, or possibly even between Earth and a future space station on its voyage to other planets. Clearly, the photon collection efficiency is a major problem over these distances. This could, for example, be circumvented by adopting an entanglement swapping scheme [12] to entangle two distant atoms – say, on the ground and in outer space – conditioned on the projection of the photon pair on an entangled state (Fig. 1a).

A second approach to establishing genuine randomness in such an experiment would rely on the use of light arriving from distant locations in the Universe to trigger the detector settings in the two measurement stations (Fig. 1b). This idea offers the advantage that the detectors need not be widely separated any more, if the triggering random signals arrive from opposite locations in the universe, such as light from distant quasars, in the extreme case.

3 Extending matter-wave interferometry

The quantum wave nature of matter was first proposed by de Broglie in 1923 [13] and soon confirmed for electrons [14, 15], atoms and diatomic molecules [16] as well as for neutrons [17]. With the development of modern molecular beam machines, ultra-cold atomic ensembles, Bose-Einstein condensates,

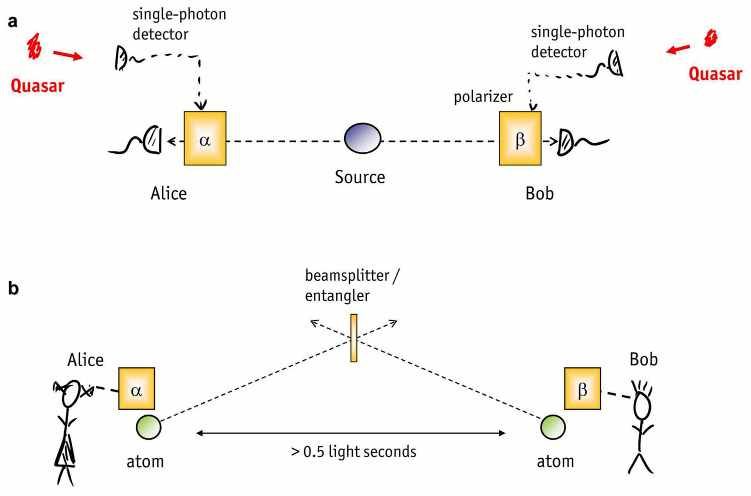

Fig. 1 (online colour at: www.fp-journal.org) Extending entangled photon experiments to long distances. (a). A possible Bell experiment that involves distant quasars to determine the local measurement settings. For example, the detection or non-detection of a photon at a certain time could serve as a basis choice. In that way, alternative explanations that invoke pre-determined settings could be narrowed down significantly. (b) A possible Bell experiment involving the free will of human observers. To ensure space-like separation between observers 'Alice' and 'Bob' will require a separation on the order of several tenths of light seconds.

laser and methods to nanofabricate diffraction masks, interference with atoms clusters and molecules have experienced a rapid evolution [18].

Recent experiments in Vienna have extended this idea to particles of increasing complexity, mass and state separation. The augmented complexity allows us to quantitatively probe new decoherence and dephasing mechanisms: Large molecules may exhibit such a rich internal complexity and high temperatures that their internal properties and state changes become measurable as a possible perturbation to the center of mass evolution, i.e. the de Broglie phases [19,20]. Interferometry with high-mass particles also holds the promise to establish new bounds on theoretical predictions that envisage modifications of standard quantum mechanics [21–25]. The first coherence experiments with internally hot fullerene molecules [26, 27] exploited far-field diffraction techniques (Fig. 2a) which were similar to those used for atoms [28] and Helium dimers [29]. The particle's polarizability enters, however, the quantum wave diffraction through the Van der Waals interaction with the diffracting grating walls [30]. This creates a conservative potential which depends on the molecule wall distance like $V_{\mathrm{vdW}} \propto r^{-3}$ and which leads to position-dependent and dispersive matter-wave phase shift. It is therefore advantageous for highly polarizable molecules to replace material gratings by optical diffraction structures as demonstrated in [31]. Even then a major technological challenge remains. Diffraction requires coherent matter waves. In the absence of cooling techniques coherence can only be provided by spatial filtering. However, collimation enormously reduces the molecular throughput.

It has therefore already been suggested by Clauser [32] that near-field Talbot-Lau interferometry could be a favorable scheme to explore the wave-particle duality of massive particles. The idea had been implemented for atoms [33] and could be extended to large molecules [34] including biodyes [35]. A Talbot-Lau interferometer does not allow to separately address the individual partial beams of the superposition state. And yet, such a device is still well adapted both for fundamental decoherence [19,20] studies and for practical force measurements [36, 37]. Even in a near-field diffraction arrangement, however, optical gratings will become unavoidable for highly polarizable particles if the grating openings are of the order of a few hundred nanometers or smaller. Correspondingly, the combination of mechanical and optical gratings is

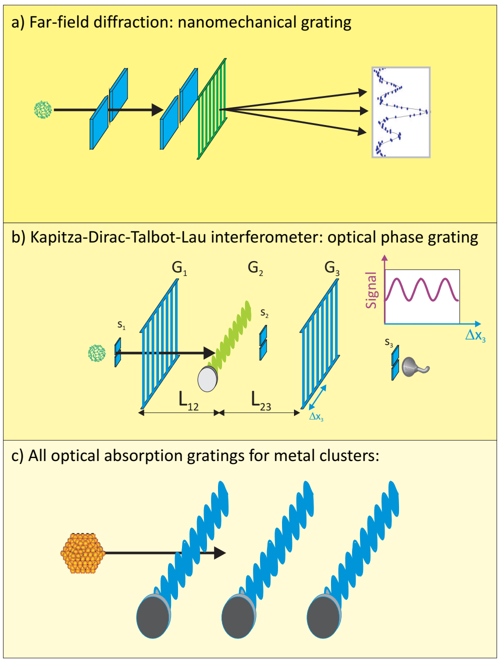

Fig. 2 (online colour at: www.fp-journal.org) Gallery of interferometers for large clusters and molecules: a far-field diffraction at a nanomechanical grating, as used for fullerenes [26, 31]; Kapitza-Dirac-Talbot-Lau interferometer [38] with a central optical phase grating; All-optical pulsed Talbot-Lau interferometer for massive metal clusters [39].

the basis for a recent development, the Kapitza-Dirac-Talbot-Lau interferometer (Fig. 2b) which allows to extrapolate matter-wave interferometry to more extended objects [38].

But what will be the ultimate mass limit for de Broglie interference experiments? The answer to this question depends on the successful development of many techniques, the availability of cold and collimated molecular beams, diffraction methods that are less sensitive to internal particle properties, efficient and selective molecule detectors for massive, neutral and slow particles as well as on the elimination of all dephasing and decoherence effects.

ionization gratings would solve many important issues in interferometry with supermassive metal clusters (see Fig. 2c). For particles in the mass range of around 1,000,000 amu fluorine lasers are expected to provide still for the foreseeable future the shortest laser wavelength in a commercially available pulsed and sufficiently intense laser source. For metals in the mass range of around 10^9 amu the absorption cross section would already grow to an extent that the high-harmonic generation of available continuous lasers could possibly also provide sufficient energy for the ionization or neutralization of the clusters. In either case we aim at creating gratings with a period of about $g = 80...100$ nm and a near-field interferometer would typically be operated in the Talbot distance, given by $L_{\mathrm{T}} = g^2/\lambda_{\mathrm{dB}}$. The minimum size of the apparatus is therefore governed by the maximum de Broglie wavelength that can be achieved. For particles as massive as 1,000,000 amu cryogenic temperatures of about 10 K should be realizable in the near future. The most probable thermal de Broglie wavelength $\lambda_{\mathrm{dB}} = h/\sqrt{2mk_BT}$ then amounts to 1 pm, which is very similar to that of the organic hot molecules in present-day experiments [37]. The Talbot length in such experiments would amount to $L_{\mathrm{T}} = 6.5$ mm. This short length is related to the use of all optical gratings and it seems still realistic to scale the interferometer length by at least a factor 100, i.e. to a total size of about one meter in a moderately sized laboratory.

This simple estimate shows already that matter interferometry with masses comparable to small rhinoviruses ($m < 1$ MDa) are no fantasy. However, metal cluster studies have many practical advantages over organic particle beams and it is also important to see that metals offer practically the highest possible mass-densities: a tobacco mosaic virus, for instance, is a tube of 300 nm length and 17 nm diameter with a mass of about 4×10^7 amu [40]. This corresponds to a density of about 1 g/cm^3. Metal densities can be more than an order of magnitude higher, with the density of gold (19 g/cm^3) as a realistic maximum. While a

300 nm long virus would already average over several potential maxima in a grating with a period of 80 nm, a 10 nm gold particle of equal mass could easily fit the experiment. All-optical gratings cannot be clogged by material particles, but they may induce gradient forces in the diffracted objects if these are too extended. We will therefore assume a preliminary hard, but possibly not insurmountable mass limit at a gold cluster of about 50 nm diameter. This corresponds to mass of roughly 10^9 amu, which is comparable to that of the much more extended bacterial DNA [41]. If it is possible to reduce the kinetic energy to the temperature equivalent of 10 K, the thermal velocity peaks at 1 cm/s and the de Broglie wavelength approaches 30 fm. This is still within the limits of a compact interferometer of 40 cm length.

One should, however, also be aware of the boundary conditions that a real experiment will face: The interferometer transit time will be as long as 40 seconds. During this time all external perturbations must be eliminated and the particles must not be deflected or dispersed by gravity. In the long run a micro-gravitational environment on board of a dedicated satellite therefore appears to be desirable. Alternatively future technological developments might also allow us to establish a non-dephasing suspension system strong enough to compensate Earth's acceleration but smooth enough not even to induce nanometer spatial shifts of the cluster trajectory over the entire transit time.

Besides the kinematic arguments given above, many dephasing and decoherence mechanisms will pose severe technical challenges at a much earlier stage. While further theoretical and experimental work is still required to provide hard limits, it is clear that the influence of Earth's gravity and rotation, interferometer vibrations, the frequency and timing jitter as well as the pointing stability of the diffracting lasers, thermal radiation from within the clusters and from the walls, collisions with the residual background gas in the vacuum chamber, fluctuations of external electro-magnetic field gradients and other parameters will have to be taken care of.

4 Superposition and entanglement in mechanical quantum systems

Another intriguing system for the study of macroscopic quantum phenomena is gradually becoming available through mechanical resonators. These devices allow us to study the collective center-of-mass motion of massive objects that contain up to 10^{20} atoms and that span the size range from hundreds of nanometers in the case of nano-electro-mechanical or nano-opto-mechanical systems (NEMS/NOMS) to tens of centimeters in the case of gravitational wave antennae [42]. It is currently a hot research topic how to prepare genuine quantum states of motion of such mechanical devices [42]. In particular the latest development in micro- and nanomechanical engineering has triggered an enormous experimental progress towards achieving this enticing goal. The broad variety of existing approaches include the coupling of mechanical systems to single electrons via spin [43] or charge [44], to Cooper pairs via microwave cavities [44, 45], or to photons inside an optical cavity [46–51]. For the latter case, quantum optics provides a well-developed toolbox to control and manipulate the state of the mechanical system via optomechanical interaction – eventually within the quantum regime.

The relevance of quantum optics for such mechanical experiments has been realized very early on and is predominantly based on two remarkable facts: first that the single-mode quantum description of an optical field is essentially equivalent to that of a harmonic oscillator, and second that the interaction between light and a mechanical oscillator can resemble a nonlinear Kerr-type interaction if the light is confined in a cavity that is modified by the mechanical motion. The latter may be implemented for example via direct changes in the cavity length [52] or using dispersion [49]. In other words, quantum optics of two optical modes that interact via a Kerr-medium can be mapped onto a quantum-opto-mechanical situation in which an optical mode and a mechanical mode interact via the transfer of photon momentum, i.e. the radiation pressure inside an optical cavity. Paolo Tombesi has been pioneering and shaping the field of quantum-opto-mechanics since its very beginning [1]. Among his contributions are the very first papers

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[1] We should not fail to mention that it was actually a talk given by Paolo Tombesi in June 2004 in Vienna that provided the final spark to start our Vienna opto-mechanics experiments.

in the 1990's on the generation of quantum effects through radiation pressure, namely the generation of squeezed light in an optomechanical cavity via the optomechanical Kerr-nonlinearity [53, 54]. Further examples include suggestions on how to utilize radiation pressure to perform photon number quantum non-demolition measurements [55,56], on mechanical quantum noise reduction via feedback techniques [57,58] – a scheme today known as cold damping or active mechanical cooling – and on the generation of non-classical states of mechanical systems by optomechanical interactions [59, 60]. With the availability of high-quality optomechanical devices these early theories have now become an important basis for a whole new field that aims at exploiting the quantum regime of mechanical resonators (Fig. 3).

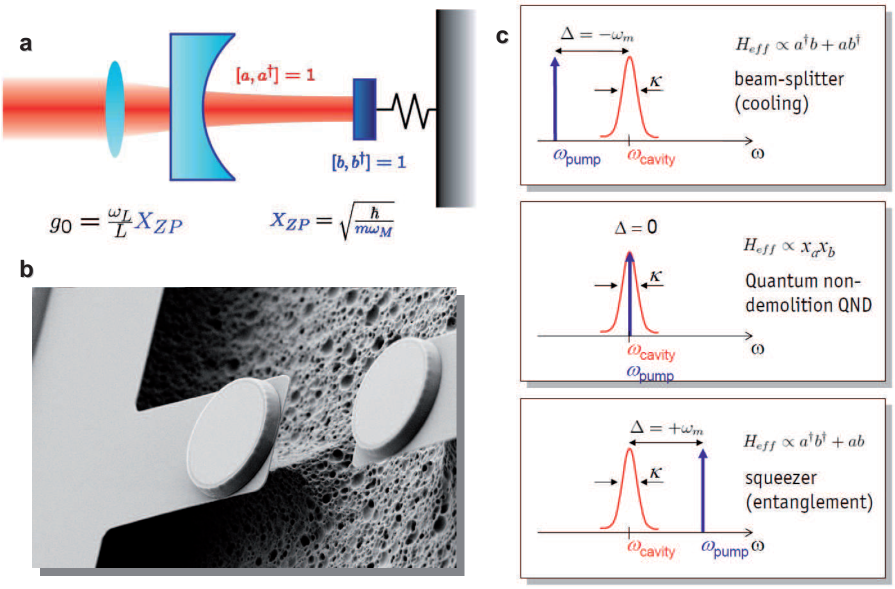

Fig. 3 (online colour at: www.fp-journal.org) Quantum optomechanics: Extending quantum experiments to massive mechanical systems. a. Working principle of cavity-optomechanics. An optical cavity mode interacts with a mechanical mode via radiation pressure. b. Micromirror design by the Vienna group at IQOQI. The fundamental mechanical mode of such a structure has recently been laser-cooled to 30 thermal quanta above the quantum ground state. c. The idea of quantum optomechanics. A strongly pumped optomechanical cavity can generate optomechanical interactions that can be tailored via the cavity detuning and that are in full analogy to quantum optics. These interactions serve as a basic toolbox to prepare mechanical quantum states by using optical quantum states.

This developing field of quantum-opto-mechanics provides – aside from numerous novel sensing and actuation technologies at and beyond the quantum limit – a unique opportunity to generate superposition states of massive mechanical systems. Some of the first conceptual ideas on this topic have been motivated by Dapprich, Penrose and Zeilinger during discussions in Innsbruck in 1997 [61,62]. Concrete experimental proposals have been suggested in form of a nanomechanical resonator coupled to a superposition state of a Cooper-pair box [63] and of a micromechanical mirror coupled to a superposition state of a single photon [64]. The main idea is to achieve sufficiently strong coupling of an individual quantum system to the mechanical resonator such that a superposition state $|0\rangle_q + |1\rangle_q$ of the quantum system generates an entangled state $|0\rangle_q|0\rangle_M + |1\rangle_q|1\rangle_M$ between photon/electron and the mechanical system. Here, $|0\rangle_M$ and $|1\rangle_M$ correspond to two coherent states of different amplitude α_0 and α_1 of the mechanical mode. If these two states can be made sufficiently distinct, i.e. $_M\langle 0|1\rangle_M = \exp[-|\alpha_1 - \alpha_0|^2] \approx 0$, one arrives at the canonical situation of Schrödinger's cat involving two macroscopically distinct motional states of a mechanical resonator.

How large can one make this separation $\Delta x \approx |\alpha_1 - \alpha_0|$ in experiments? For a crude quantitative estimate we can assume that the mechanical displacement Δx is given by $\Delta x = F/k$, where F is the force applied by the quantum system and $k = m\omega_m^2$ is the mechanical spring constant (m: mode mass, $\omega_m/2\pi$: mechanical mode frequency). Typical forces that should be feasible to achieve are on the order of some 10^{-18} N (aN). For example, a single photon of wavelength $\lambda = 1064$ nm inside a 30 mm long cavity exerts a radiation pressure force of approx. 6 aN to the walls of the cavity [2]. If one of the walls consists of a micromechanical mirror of fundamental resonance frequency ω_m, maintaining the force over a mechanical period $T = 2\pi/\omega_m$ results in a displacement of the above Δx. This means that for an optical cavity finesse of 5×10^6 (i.e. a cavity lifetime of 1 ms) one can generate the maximum displacement for a mode at $\omega_m/2\pi \approx 1$ kHz. Assuming a mode mass of $m = 1$ ng (i.e. a spring constant $k \approx 4 \times 10^{-5}$ Nm^{-1}) the radiation pressure force displaces the mechanics by $\Delta x/x_{\text{ZP}} \approx 1$ or $\Delta x \approx 1.5 \times 10^{-13}$ m, which is smaller than a typical crystal unit cell (≈ 2–5 Å). In this scenario, significantly larger displacements are possible only either by increasing the finesse (hence allowing for larger forces at smaller cavity lengths or for longer photon-lifetimes at smaller resonator frequencies) or by decreasing the resonator mass. For example, lowering the mass in this explicit scenario by two orders of magnitude, at otherwise unchanged parameters, would result in $\Delta x/x_{\text{ZP}} \approx 10$ or $\Delta x \approx 1.5 \times 10^{-11}$ m. As one will certainly have to find a trade-off between size and optical coupling it remains to be seen which combination of experimental parameters can eventually be realized. It is interesting to note that other coupling mechanisms produce forces of similar order of magnitude. For example, capacitive coupling of a mechanical resonator to a Cooper pair box can generate forces of up to 50 aN in today's devices [44, 45] and magnetic coupling to single atomic spins can reach similar values [43, 65][3]. As a general rule of thumb one can estimate the displacement $\Delta x/x_{\text{ZP}} = F/(kx_{\text{ZP}}) = F/(\hbar^{1/2}m^{1/2}\omega_m^{3/2})$, as long as the interaction time exceeds one mechanical period $T = 2\pi/\omega_m$. This raises the intriguing question whether it will be possible to generate macroscopic displacements that exceed the physical size of the mechanical object. In principle yes: assuming a mechanical object of mass $m = 10^{-21}$ kg and resonance frequency $\omega_m/2\pi = 10^5$ Hz, which could be realized for example via a carbon nanotube or a silicon nanowire, a force of 50 aN would be sufficient to generate a displacement $\Delta x/x_{\text{ZP}} \approx 300$ or $\Delta x \approx 100$ nm, i.e. larger than the object's typical extensions of a few nm.

While we have argued above that macroscopically distinct superposition states of mechanical resonators should be possible in principle, there remain at present several challenges that have to be overcome:

First, the coupling between mechanics and quantum system has to be maintained suffciently long to achieve the wanted displacement in the mentioned scenarios. To be more precise, the coupling rate $g_0 = \frac{Fx_{ZP}}{\hbar}$ has to overcome both the individual systems' decoherence rates (strong coupling regime) and the mechanical frequency. The strong coupling regime of a mechanical resonator has only recently been realized for the first time between a micromechanical system and the high-intensity laser field of an optical cavity [66]. Achieving the single-photon strong coupling regime is still an outstanding challenge and optical finesse values exceeding 10^6 may be required. New experimental approaches involving photonic crystal cavities could be very promising systems to achieve this [67, 68]. Other interesting proposals to obtain a strong coupling rely on the magnetic coupling to single spins located in nitrogen vacancy centers [65].

Second, the mechanical thermal decoherence rate $\Gamma = (k_B T)/(\hbar Q)$ (T: bath temperature; k_B: Boltzmann's constant; Q: mechanical quality factor) needs to be minimal, ideally well below both the coupling rate g_0 and the mechanical frequency ω_m. Current experiments with micromechanical resonators are operated in a ^{4}He environment (4 K) and have achieved $\Gamma \approx 25$ MHz. For typical dilution refrigerator environments ($T \approx 50$ mK) and Q-factors on the order of 10^6, as has been observed in recent nanoelectromechanical experiments, one obtains $\Gamma \approx 6$ kHz. Current research focuses on further increasing the mechanical quality factor [69–71].

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[2] The radiation pressure force is given by the photon momentum transfer per cavity roundtrip time, i.e. $F_{RP} = \frac{2\hbar\omega_c}{L}$ with the cavity frequency $\omega_c = 2\pi c/\lambda$.

[3] Assuming magnetic field gradients of 10^7T m^{-1} and a working distance of 20 nm.

Third, operation close to the mechanical quantum ground state is desirable to avoid thermally mixed states. This requires mode temperatures T_{eff} on the order of $\frac{\hbar\omega_m}{k_B}$, i.e below 50 nK (5 μK) for a 1 kHz (100 kHz) resonator. While this is hard to achieve with conventional cryogenic equipment, additional cooling techniques such as active cooling (cold damping) [58, 72, 73] or mechanical laser cooling based on backaction [47, 48, 51, 74, 75] are now available. There, cooling down to 30 quanta for micromechanical systems coupled to optical cavities [66, 76] and down to 4 quanta with nanomechanical systems coupled to microwave cavities [77] has been observed. As we (MAs, AZ) have shown in a joint work with Paolo Tombesi, a proper application of mechanical laser cooling to a suffciently broadband cavity can result in the direct generation of optomechanical entanglement [78, 79].

On a final note we should mention that detecting such macroscopic mechanical superposition states might be similarly challenging as preparing them. This is because standard quantum physics predicts that they decohere at a rate that is proportional to the square of their macroscopic displacement Δx. To be precise: because of the unavoidable coupling to the oscillator's environment (such as coupling to the mechanical clamping supports, coupling to internal defects, etc.), the overall quantum mechanical decoherence rate is given by $\Gamma_{\text{QM}} = \Gamma(\Delta x/x_{ZP})^2$ [80–82][4]. For the last example given above this means that we have to expect a speed up of the thermal decoherence Γ by almost five(!) orders of magnitude. Minimal thermal decoherence rates Γ are therefore indispensable. We are only at the beginning of exploring all these questions in actual experiments. It is clear that the quantum regime of mechanical systems provides fascinating opportunities to study macroscopic quantum physics. It is also clear that the absence of quantum phenomena at these scales can easily be created by quantum physics itself and that any such effects in experiments will require an extremely careful analysis.

5 Conclusion

We have provided a brief outlook on possible extensions to current quantum experiments. The discussed examples include distance in the case of photons and mass, size and complexity in the case of matter-waves and mechanical systems. These extensions will provide tests of quantum theory in a hitherto untested parameter regime and with new boundary conditions for alternative explanations – for example by involving human decisions in a Bell experiment or by guaranteeing noninvasive measurability in a Leggett-Garg experiment [83]. In that sense, such experiments will allow to address new aspects in the foundational questions of quantum theory. Evidently, such experiments provide an enormous challenge, but they might be worthwhile considering the fundamental issues for our world view at stake.

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