Matter-wave optics: Observing an ultracold atomic cloud expanding in free fall

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This Highlight showcases the Research Paper entitled *Collective-Mode Enhanced Matter-Wave Optics* (Phys. Rev. Lett. **127**, 100401 (2021), DOI: 10.1103/PhysRevLett.127.100401)

Quantum mechanics entails several concepts incompatible with classical mechanics that appear counter-intuitive if not bizarre. The "spooky action at a distance" which results from the phenomenon of quantum entanglement is an oft-cited example. The concept of wave-particle duality is another one. While, at first, the idea of a particle wave raised eyebrows as a mathematical artefact, it made serious inroads in the 1920th, when Louis de Broglie put forward a simple formula for the wavelength (now referred to as the de Broglie wavelength λ_{dB}) of a matter wave [1], predicting that it equals the product of Planck's constant h and the inverse of the classical momentum $p = mv$ of a particle of mass m and velocity v,

$$\lambda_{\mathrm{dB}} = \frac{h}{mv} \,. \tag{1}$$

De Broglie's bold relativistic derivation of his formula motivated experimentalists to seek evidence for the existence of matter waves. As diffraction and interference are unambiguous manifestations of wave behavior, their observation could have served as the smoking gun of matter waves. As de Broglie wavelengths of both electrons (at suitable energies) and neutral atoms (at thermal energies) are minute, the first successful experiments revealing the particles' wave nature employed diffraction by crystals, taking advantage of their likewise microscopic lattice scales. First, in 1927 Clinton Davisson and Lester Germer reported experimental evidence for diffraction of electrons by a nickel crystal [2, 3]. Shortly thereafter Otto Stern, together with Immanuel Estermann, was able to present unambiguous evidence for diffraction of molecular beams of He and H_2 from a LiF crystal surface [4]. Providing evidence for matter-wave behavior, these experiments confirmed within an accuracy of 1% de Broglie's wave description, thereby marking the beginning of matter-wave optics.

Just months after de Broglie's work appeared another no less astounding quantum effect was predicted by Albert Einstein [5], based on the work of Satyendra Nath

Bose that Einstein translated into German one year earlier [6]. The predicted effect came to be known as Bose-Einstein condensation or, for short, BEC. However, unlike de Broglie's matter waves, none of the contemporary scientists thought it possible to observe BEC in a real experiment as the experimental conditions required were out of reach in the 1920th. It took 70 years when, in 1995, three labs in the U.S.A. were able to observe BEC in small ultracold dilute gas clouds of rubidium [7], lithium [8], and sodium [9]. In 2001, Eric A. Cornell, Wolfgang Ketterle, and Carl E. Wieman shared the Nobel Prize in Physics "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".

The phenomenon of BEC is intimately connected with wave-like behavior of particles in the quantum domain. At thermal energies, gaseous atoms move with fairly high velocity, and de Broglie wavelengths are minute with respect to all other relevant length scales of the gas. As a result, quantum effects are usually negligible at these conditions. At sufficiently low temperatures, however, where the motion of atoms in a gas is greatly slowed down, de Broglie wavelengths become correspondingly large. In a simplified picture of BEC formation upon cooling of a gas, one can consider the atoms' de Broglie wavelengths becoming about as large as the average distance between the atoms. At this point, the quantum wave nature begins to play a decisive role as matter waves of individual atoms are no longer independent, but begin to overlap. Below a density-dependent critical temperature, this leads to the formation of a single macroscopic quantum state described by a wave-function of the part of the gas that BE-condensed. The first BEC was observed in a dilute Rb gas at a temperature as low as 170 nK [7]. This explains why it took experimentalists seven decades to catch up with Einstein's prediction. They had to develop sophisticated techniques to bring an atomic vapor to such extremely low temperatures, suppressing the vapor's predilection for forming a liquid or solid phase already at way higher temperatures.

From 1995 on, experimental studies with BEC in dilute gases have boomed in labs around the world. Since then, BEC has been observed for a variety of elements, and new techniques to investigate the quantum properties of the condensates and to take advantage of these very properties have been developed. Already in 1997, the coherence properties of BEC were revealed when a fringe-pattern, resulting from interference of two independent condensates that were maneuvered to overlap, was observed [10]. Early atom interferometers were based on thermal atomic beams that could be split and sent along two or more paths and brought back together to overlap in space and time and interfere [11, 12]. These beam-based atom interferometers had already enabled several investigations of hitherto unprecedented sensitivity [13]. However, using Bose-Einstein condensates instead of a thermal atom beam as the source in a matter-wave interferometer opened the floodgates of a new generation of studies that take advantage of the phase sensitivity of an interferometer.

Due to its minute temperature, a BEC, when released from its electromagnetic confinement, expands slowly. This makes it possible to observe expansion and interference over relatively long times that are crucial as they can greatly enhance the sensitivity of the matter-wave interferometer. For instance, in a Mach-Zehnder-type interferometer, the phase is proportional to the square of the separation time. In a typical lab setup, the observation time is, however, limited by gravity which causes the atoms to simply fall down. Long free-expansion times have been demonstrated in atom interferometers where a Bose-Einstein condensed cloud is launched upwards in a 10 m vertical vacuum pipe by optical forces from laser fields (atomic fountain) [14]. Even then, the observation time is limited to roughly 2 seconds. In addition, gravitational sag can also lead to deformations of the trapping potentials used in an experiment.

In order to circumvent these limitations, experimentalists have started performing BEC and atom-interferometry experiments in microgravity. To this end, the apparatus could be carried by an airplane on a parabolic flight trajectory and allowing for roughly 20 s of weightlessness, as successfully demonstrated by a French collaboration [15, 16]. An alternative approach to achieving microgravity was pursued at the drop tower of ZARM, the Center of Applied Space Technology and Microgravity at the University of Bremen in Germany (see Fig. 1), where a single drop provides 4.7 s of microgravity [17]. In the paper by Deppner et al. [18] highlighted herein, a collaboration of experts from five German and two French institutions reports on most recent results from the drop tower microgravity experiments. In a total of 34 drops, BEC's of 100,000 Rb atoms were prepared on an atom chip at weightlessness. Releasing the BEC from its trapping fields during free fall, an expansion free of gravitational pull corresponding to an effective gas temperature of just 2 nK could be observed. The collaboration succeeded in tailoring the expansion by (1) excitation of a collective mode of a quadrupole oscillation and releasing the BEC at a well chosen phase of this collective oscillation. This was combined with (2) a magnetic lens that was switched on for just 2.4 ms in the early phase of the free expansion, functioning as a time-domain matter-wave lens. For a well chosen release phase and strength of the magnetic lens, a very slow expansion corresponding to a temperature of only 38 pK was achieved. This made it possible to observe the expansion for as long as 2 seconds.

The results presented by Deppner et al. [18] pave the way for free-expansion experiments lasting ten or more seconds. This will be relevant for experiments in space where much longer observation times can be exploited. The first step to matter-wave interferometry in space was made in 2017 when the MAIUS-1 (Matter-Wave Interferometry in Microgravity) rocket was launched [19, 20]. The ballistic rocket, launched in the north of Sweden, brought the scientific apparatus to an altitude of $\approx$ 250 km. The corresponding flight time of 6 min in space (altitude > 100 km) permits to take full advantage of the maximum observation times enabled by the method of Deppner et al. [18]. Beyond the rocket-based experiments there are plans for an extended experimental setup on the International Space Station (ISS). In 2025 the existing CAL (Cold Atom Laboratory) on ISS will be upgraded to BECCAL, a NASA-DLR collaboration [21]. Exactly 100 years after Einstein's prediction, this might bring BEC experiments to a new level of sophistication. Future applications of matter-wave interferometers in space will range from high-precision BEC interferometry for fundamental physics, such as for instance, tests of the equivalence principle [22], to further potential applications including, e.g., navigation and earth observation.

References

1. de Broglie, L. (1925) Recherches sur la théorie des quanta. *Annales de Physique* **10**, 22–128.
2. Davisson, C & Germer, L. H. (1927) The scattering of electrons by a single crystal of nickel. *Nature* **119**, 558.
3. Davisson, C & Germer, L. H. (1927) Diffraction of electrons by a crystal of nickel. *Phys. Rev.* **30**, 705–740.
4. Estermann, I & Stern, O. (1930) Diffraction of molecular beams. *Zeitschrift für Physik* **61**, 95–125.
5. Einstein, A. (1925) Quantentheorie des einatomigen idealen Gases. *Sitzungsber. Preuss. Akad. Wiss., Mathem.-Naturwiss. Kl.* **23**, 3–14.
6. Bose, S. N. (1924) Plancks Gesetz und Lichtquantenhypothese. *Zeitschrift für Physik* **26**, 178–181.
7. Anderson, M. H, Ensher, J. R, Matthews, M. R, Wieman, C. E, & Cornell, E. A. (1995) Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor. *Science* **269**, 198–201.
8. Bradley, C. C, Sackett, C. A, Tollett, J. J, & Hulet, R. G. (1995) Evidence of Bose-Einstein Condensation in an Atomic Gas with Attractive Interactions. *Phys. Rev. Lett.* **75**, 1687–1690.
9. Davis, K. B, Mewes, M. O, Andrews, M. R, VanDruten, N. J, Durfee, D. S, Kurn, D. M, & Ketterle, W. (1995) Bose-Einstein Condensation in a Gas of Sodium Atoms. *Phys. Rev. Lett.* **75**, 3969–3973.
10. Andrews, M. R, Townsend, C. G, Miesner, H. J, Durfee, D. S, Kurn, D. M, & Ketterle, W. (1997) Observation of interference between two Bose condensates. *Science* **275**, 637–641.
11. Keith, D. W, Ekstrom, C. R, Turchette, Q. A, & Pritchard, D. E. (1991) An interferometer for atoms. *Phys. Rev. Lett.* **66**, 2693.
12. Carnal, O & Mlynek, J. (1991) Young's double-slit experiment with atoms: A simple atom interferometer. *Phys. Rev. Lett.* **66**, 2689.
13. Cronin, A. D, Schmiedmayer, J, & Pritchard, D. E. (2009) Optics and interferometry with atoms and molecules. *Rev. Mod. Phys.* **81**, 1051–1129.
14. Kovachy, T, Asenbaum, P, Overstreet, C, Donnelly, C. A, Dickerson, S. M, Sugarbaker, A, Hogan, J. M, & Kasevich, M. A. (2015) Quantum superposition at the half-metre scale. *Nature* **528**, 530–533.
15. Stern, G., Battelier, B., Geiger, R., Varoquaux, G., Villing, A., Moron, F., Carraz, O., Zahzam, N., Bidel, Y., Chaibi, W., Pereira Dos Santos, F., Bresson, A., Landragin, A., & Bouyer, P. (2009) Light-pulse atom interferometry in microgravity. *Eur. Phys. J. D* **53**, 353–357.
16. Barrett, B, Antoni-Micollier, L, Chichet, L, Battelier, B, Lévèque, T, Landragin, A, & Bouyer, P. (2016) Dual matter-wave inertial sensors in weightlessness. *Nature Communications* **7**, 13786.
17. Müntinga, H, Ahlers, H, Krutzik, M, Wenzlawski, A, Arnold, S, Becker, D, Bongs, K, Dittus, H, Duncker, H, Gaaloul, N, Gherasim, C, Giese, E, Grzeschik, C, Hänsch, T. W, Hellmig, O, Herr, W, Herrmann, S, Kajari, E, Kleinert, S, Lämmerzahl, C, Lewoczko-Adamczyk, W, Malcolm, J, Meyer, N, Nolte, R, Peters, A, Popp, M, Reichel, J, Roura, A, Rudolph, J, Schiemangk, M, Schneider, M, Seidel, S. T, Sengstock, K, Tamma, V, Valenzuela, T, Vogel, A, Walser, R, Wendrich, T, Windpassinger, P, Zeller, W, van Zoest, T, Ertmer, W, Schleich, W. P, & Rasel, E. M. (2013) Interferometry with Bose-Einstein condensates in microgravity. *Phys. Rev. Lett.* **110**, 093602.

18. Deppner, C, Herr, W, Cornelius, M, Stromberger, P, Sternke, T, Grzeschik, C, Grote, A, Rudolph, J, Herrmann, S, Krutzik, M, Wenzlawski, A, Corgier, R, Charron, E, Guéry-Odelin, D, Gaaloul, N, Lämmerzahl, C, Peters, A, Windpassinger, P, & Rasel, E. M. (2021) Collective-mode enhanced matter-wave optics. *Phys. Rev. Lett.* **127**, 100401.
19. Becker, D, Lachmann, M. D, Seidel, S. T, Ahlers, H, Dinkelaker, A. N, Grosse, J, Hellmig, O, Müntinga, H, Schkolnik, V, Wendrich, T, Wenzlawski, A, Weps, B, Corgier, R, Franz, T, Gaaloul, N, Herr, W, Lüdtke, D, Popp, M, Amri, S, Duncker, H, Erbe, M, Kohfeldt, A, Kubelka-Lange, A, Braxmaier, C, Charron, E, Ertmer, W, Krutzik, M, Lämmerzahl, C, Peters, A, Schleich, W. P, Sengstock, K, Walser, R, Wicht, A, Windpassinger, P, & Rasel, E. M. (2018) Space-borne Bose–Einstein condensation for precision interferometry. *Nature* **562**, 391–395.
20. Lachmann, M. D, Ahlers, H, Becker, D, Dinkelaker, A. N, Grosse, J, Hellmig, O, Müntinga, H, Schkolnik, V, Seidel, S. T, Wendrich, T, Wenzlawski, A, Carrick, B, Gaaloul, N, Lüdtke, D, Braxmaier, C, Ertmer, W, Krutzik, M, Lämmerzahl, C, Peters, A, Schleich, W. P, Sengstock, K, Wicht, A, Windpassinger, P, & Rasel, E. M. (2021) Ultracold atom interferometry in space. *Nature Communications* **12**, 1317.
21. Frye, K, Abend, S, Bartosch, W, Bawamia, A, Becker, D, Blume, H, Braxmaier, C, Chiow, S.-W, Efremov, M. A, Ertmer, W, Fierlinger, P, Franz, T, Gaaloul, N, Grosse, J, Grzeschik, C, Hellmig, O, Henderson, V. A, Herr, W, Israelsson, U, Kohel, J, Krutzik, M, Kürbis, C, Lämmerzahl, C, List, M, Lüdtke, D, Lundblad, N, Marburger, J. P, Meister, M, Mihm, M, Müller, H, Müntinga, H, Nepal, A. M, Oberschulte, T, Papakonstantinou, A, Perovs?ek, J, Peters, A, Prat, A, Rasel, E. M, Roura, A, Sbroscia, M, Schleich, W. P, Schubert, C, Seidel, S. T, Sommer, J, Spindeldreier, C, Stamper-Kurn, D, Stuhl, B. K, Warner, M, Wendrich, T, Wenzlawski, A, Wicht, A, Windpassinger, P, Yu, N, & Wörner, L. (2021) The Bose-Einstein condensate and cold atom laboratory. *EPJ Quantum Technology* **8**, 1.
22. Asenbaum, P, Overstreet, C, Kim M., Curti, J, & Kasevich, M. A. (2020) Atom-interferometric test of the equivalence principle at the 10^{-12} level. *Phys. Rev. Lett.* **125**, 191101.

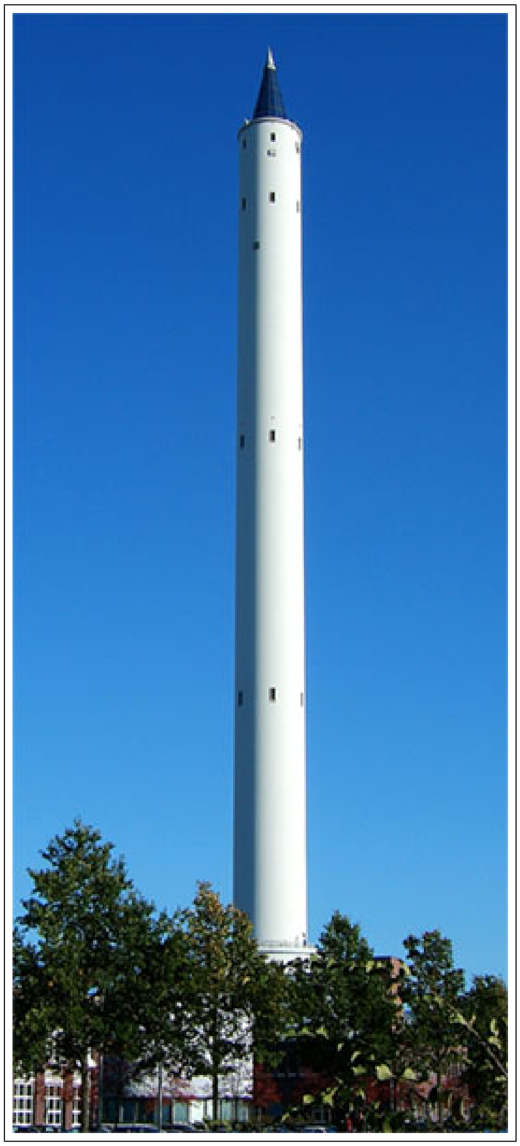

Fig. 1: The 144 m tall drop tower at ZARM (Center of Applied Space Technology and Microgravity), University of Bremen, Germany. The BEC experiments reported by Deppner et al. (Phys. Rev. Lett. **127**, 100401 (2021)) were performed in a total of 34 drops of 110 m in vacuum corresponding to a free-fall time of 4.74 s. Photograph from Wikipedia by CuttyP, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=745805