

better cohesion between the repair layer and the underlying concrete. This improved bonding makes the interface less vulnerable and extends the life of the repair. The growth of this, and the industrial high-pressure cleaning market, have meant that the pumping and other support equipment, which were items of high cost and poor reliability over a decade ago, are now less expensive and equipment now reliably operates commercially at pressures above 280 MPa (41,000 lb/in.²). With the growth of these industrial markets, the relatively small market that mining represents has limited development in this field.

Waterjets do, however, have several unique advantages, such as the ability to transmit energy down very small flexible conduits, and the low levels of force required to direct the stream. Thus, in specialized operations, high-pressure tools are starting to find a market.

Quarrying. The first market for specialized high-pressure tools was in the use of waterjets to cut granite

ite (see *illus.*). Although first investigated a number of years ago, it has been only recently that waterjet quarrying of stone has become a commercial reality. As with other applications, there is a significant trade-off between pressure and flow rate choices in selecting the best tool for the operation. Waterjets can cut into typical granite, based on crack growth around the crystal interfaces, at pressures of 70–100 MPa (10,000–14,500 lb/in.²). One of the earlier demonstrations that this was a practical tool came with the carving of the Missouri Stonehenge at the University of Missouri-Rolla. More recently, this has been followed by the carving of the Millennium Arch, a sculpture in which the figures of a man and a woman have been carved from the legs of a 5-m-high (16-ft) arch and the figures have then been polished and positioned some 15 m (50 ft) away.

The precision cutting and minimization of waste that this demonstrates has particular benefit in the dimension stone (cut into shaped blocks) business. Although the granite resources apparently available to quarry owners are large, at any given site this is only superficially true. The granite is not a consistently homogeneous rock. It has varying properties with direction, and frequently contains flaws, fissures, or layers of rock of different color and consistency, which reduce the volume available to market. Given that the primary quarrying method uses flame torches, which channel into the rock with a slot wider than the sole of the operators shoe, and add to this the zone of heat-weakened rock left on the side of the cut, the cutting operation is expensive. Add to this the health and safety concerns of the "old" technology—noise levels of around 140 dB and the generation of fine clouds of dust with the risk of respiratory problems—and a clear technical need becomes evident.

Over the past 4 years this need has increasingly been met by the use of an oscillating jet lance, which cuts into the granite at a pressure of around 250 MPa (38,000 lb/in.²). A flow rate of about 27 liters/min (7 gal/min) is directed through a single nozzle, which oscillates over the face of the slot as it is fed up and down its length. Typically, the slots are some 3–5 m (10–16 ft) deep, and the machine has been automated, so that the lance will advance into the cut to an initial distance of some 6 m (20 ft). After this, the machine can be moved forward again, so that overall lengths of more than 30 m (100 ft) have been created as primary cuts in the quarry floor. From these, blocks can then be isolated and removed from the solid for processing into slabs for commercial use. Cutting rates vary between 1 and 1.75 m²/h (11 and 19 ft²/h) as a function of the granite type, which is roughly 25–50% higher than the burner production rates in the same stone. The slots are some 4–7 cm (1.6–2.8 in.) wide, but because of the lack of damage to the walls, the block surfaces can be used as the starting surface for subsequent processing.

The machines that have been installed in both the United States and Europe are fully automated so that several machines may be controlled by a single

operator who does not have to be present during the operation, but who may be summoned at the end of a cut or if a problem arises. The noise level (98 dB) is considerably less than that of the flame burner. Depending on the granite, the cost benefit will also vary, but figures of \$49.62/m² as opposed to \$73.83 m² for a burner have been quoted.

Drilling. Slot cutting is a narrow niche market for waterjet use. The flexibility of the tool in applying high cutting pressures at the end of a small, possibly flexible cutting head makes the tool potentially useful for drilling. The most significant work in this field is taking place in Australia, although much of the pioneering effort took place in the United States. To illustrate the benefits that can come from the use of waterjets, consider the need to drill out from vertical well bores in order to more effectively recover oil or gas from a reservoir. A flexible high-pressure hose can make a turn from vertical to horizontal in a tight radius (around 20 cm; 8 in.) and transmit power to a drill so that it might advance over half a kilometer into coal to allow recovery of methane. Premining methane has both economic and safety benefits which are now being pursued commercially after development, first at the University of Missouri-Rolla, and then at the Center for Mining Technology & Equipment in Brisbane, Australia.

For background information see COAL MINING; DRILLING AND BORING, GEOTECHNICAL; GRANITE; MINING; PLACER MINING in the McGraw-Hill Encyclopedia of Science & Technology. David A. Summers Bibliography. A. W. Momber, *Water Jet Applications in Construction Engineering*, Balkema, Rotterdam, 1998; D. A. Summers, *Waterjetting Technology*, E & FN Spon, 1995; R. A. Tikhomirov et al., *High-Pressure Jet Cutting*, transl. from the Russian by V. Berman, ASME Press, New York, 1992.

Wave-particle duality

A fundamental tenet of quantum mechanics is that every particle also has a wave nature and every wave also has a particle nature, at least in principle. For light, which in classical physics is an electromagnetic wave, the particle nature was first postulated by Albert Einstein in 1905, after Max Planck's introduction of the quantum of action in 1900. The particles of light are now called photons and have found abundant experimental confirmation.

For massive particles, the wave nature was first postulated by Louis de Broglie in 1924. For a particle of mass m and speed v , the de Broglie wavelength is $\lambda_{dB} = h/mv$, where $h = 6.6 \times 10^{-34}$ J · s is Planck's quantum of action.

The wave nature of matter has found experimental confirmation for many, very diverse particles, from electrons and neutrons to atoms and most recently even for molecules as complex as the fullerenes C₆₀ and C₇₀. While diffraction of matter waves, particularly of electrons and neutrons, has become a standard tool in many areas such as nuclear physics,

atomic physics, and solid-state physics, the wave-particle duality itself continues to be of fundamental philosophical significance.

Double-slit experiment. The essence of wave-particle duality emerges in discussing the famous double-slit experiment (Fig. 1). As a Gedanken (thought) experiment, it was already a tool in the debate between Einstein and Niels Bohr about epistemological questions in quantum mechanics. Radiation, be it light or massive particles, passes a diaphragm with two openings. Behind the diaphragm, fringes are observed which can be explained as being due to interference of waves passing the two slits. The interference is also observed when the intensity is so low that the particles are detected one by one. The observed interference fringes on the detection screen can be calculated via the appropriate wave function, whose square gives the probability to observe a particle at a given location. This naturally implies that the interference fringes will also be obtained if they are recorded individual particle by individual particle.

The philosophical conundrum arises when preconceived classical notions are applied to an analysis of this experiment. For example, if the particles are thought of as localized entities, they must pass through either slit to arrive at the observation screen. But how can an individual particle know whether the other slit is open or not? The modern interpretation, suggested by Bohr, is that one should not talk about a specific property of a quantum object

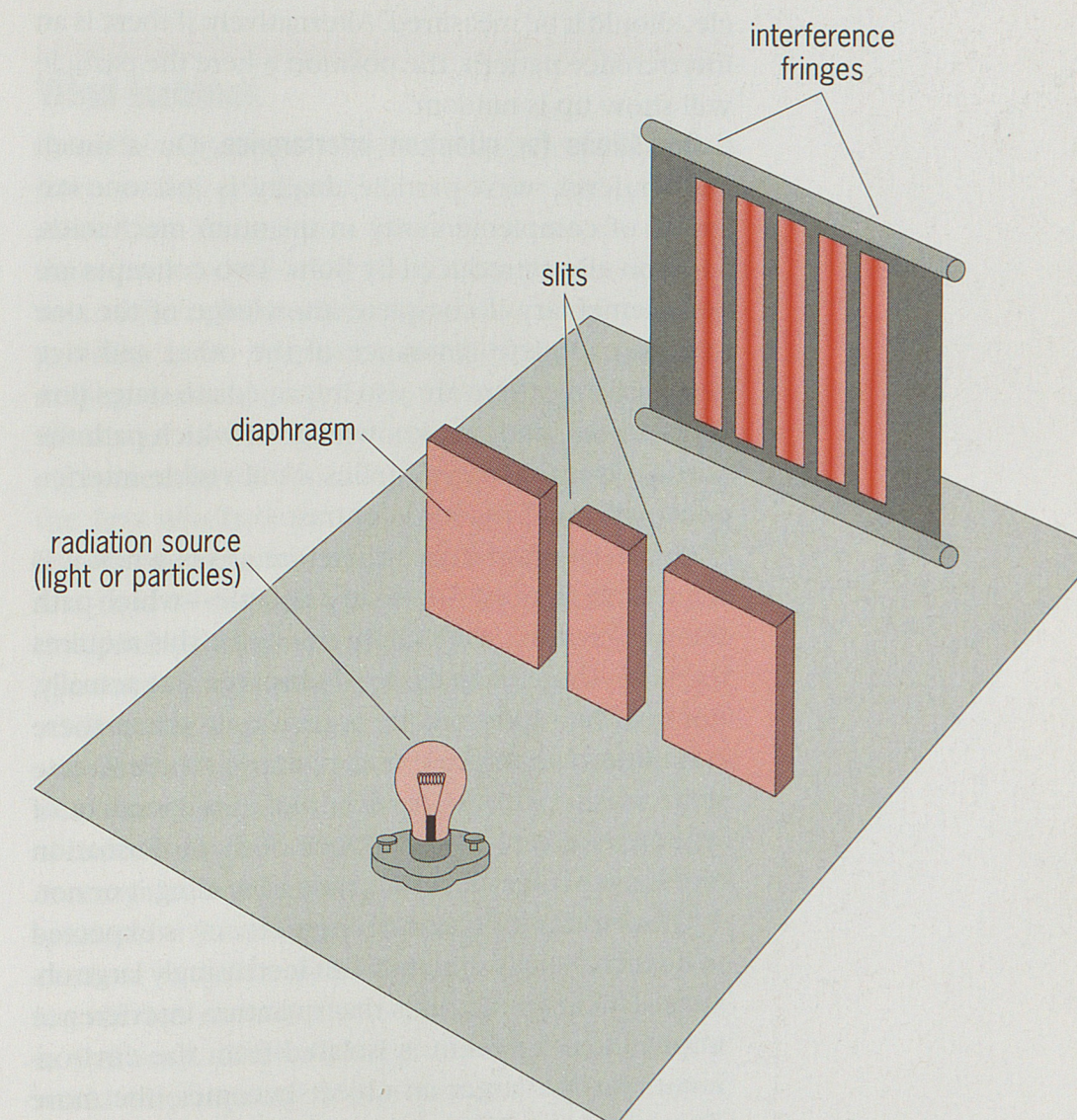
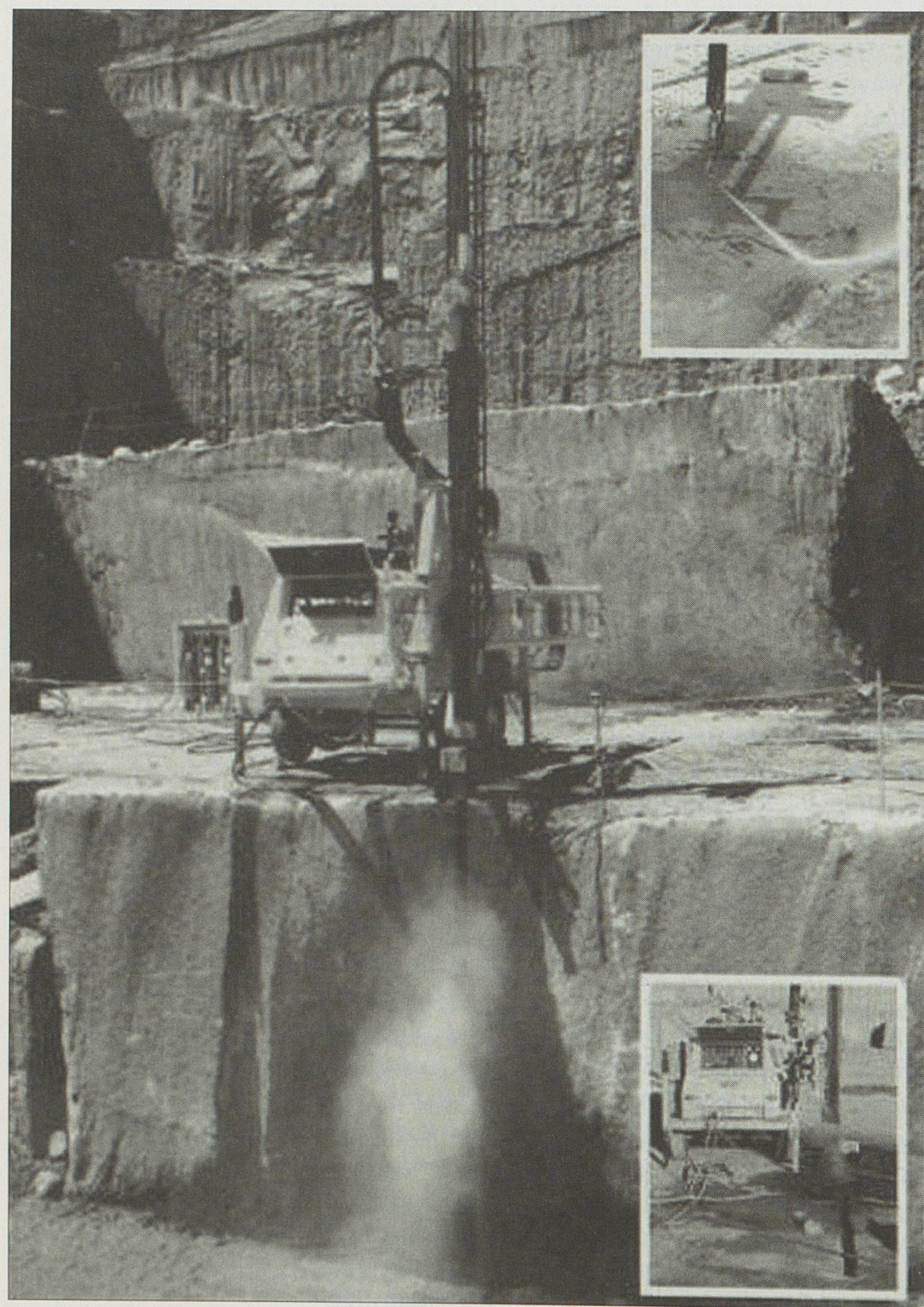


Fig. 1. Principle of the double-slit interference experiment, showing wave-particle duality.



High-pressure waterjets are used to outline granite blocks in a quarry. (NED Corp.)

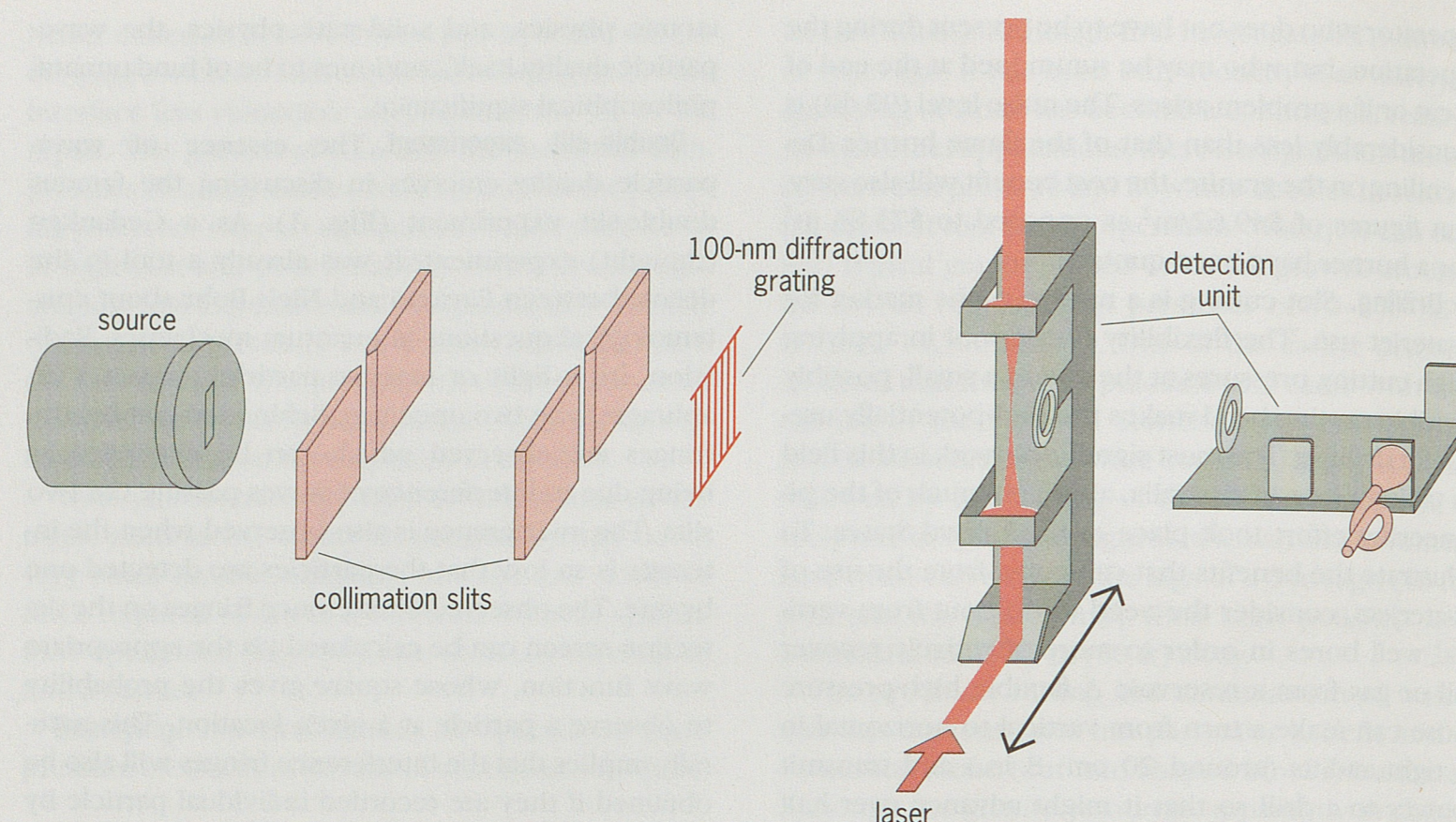


Fig. 2. Principle of the fullerene interference experiment.

without explicitly specifying the apparatus to determine that property.

The experimentalist therefore decides between the wave and the particle properties in the experiment by choosing the appropriate apparatus. Nature then gives a random answer for the single outcome within the probabilities given by the wave function. For example, with equal probability either one of the two slits will result as the location of the particle, should it be measured. Alternatively, if there is an interference pattern, the position where the particle will show up is random.

Conditions for quantum interference. On a much deeper level, wave-particle duality is just one example of complementarity in quantum mechanics, a notion also introduced by Bohr. Two concepts are complementary if complete knowledge of the one implies complete ignorance of the other and vice versa. Clearly, there are also intermediate states possible. Partial but fuzzy knowledge of which path the particle went through implies a still visible interference pattern of reduced contrast.

Quantum interference therefore arises when it is impossible to know—even in principle—which path the particle took. One might think that this requires the knowledge of an external observer. But actually, full quantum interference is seen only when there is no information present anywhere in the universe as to which path the particle took, independent of whether we care to take notice of that information or even whether we are capable of reading it or not.

Observation of quantum interference is expected to be increasingly difficult with increasingly large objects. The main reason is that quantum interference implies that a system is isolated from the environment; yet the larger an object becomes, the more degrees of freedom it has, that is, the more easily it exchanges information with the environment.

Fullerene interference experiment. The experiment with the most massive and complex objects showing de Broglie interference thus far (Fig. 2) was successful with the fullerene molecules C_{60} and C_{70} (although the curves shown here are for C_{60} only). The fullerenes were evaporated in an oven at a temperature of around 900 K (1160°F). They passed through fine collimation slits and transversed a silicon nitride grating whose bars were spaced at a period of 100 nanometers with 50-nm openings. The interference pattern was observed by scanning a very fine ionizing laser beam across the molecular beam. The ions were recorded as a function of the laser position.

This experiment has a number of interesting features: (1) The de Broglie wavelengths of 2–4 picometers are more than 100 times smaller than the size (1 nm) of the fullerenes, indicating that size itself is not crucial. (2) In the experiment resulting in Fig. 3a, the fullerenes still have their full thermal velocity distribution. Nevertheless, it is possible to clearly observe the interference pattern. (3) Because of the high temperature of the fullerenes, each individual molecule is in a quantum state different from all other molecules, as their rotational and vibrational degrees of freedom are highly excited. By that very feature alone, different fullerenes cannot interfere with each other. The experiment is truly a single-particle interference phenomenon. This is also guaranteed by the low intensity of the fullerene beam in the experiment. (4) Most importantly, again because of the high temperature of the fullerenes, they are not completely isolated from the environment. Indeed, each fullerene is expected to emit a few photons on its path from the oven to the plane of observation.

Then, why do these photons not disturb the interference pattern? The answer is obtained simply

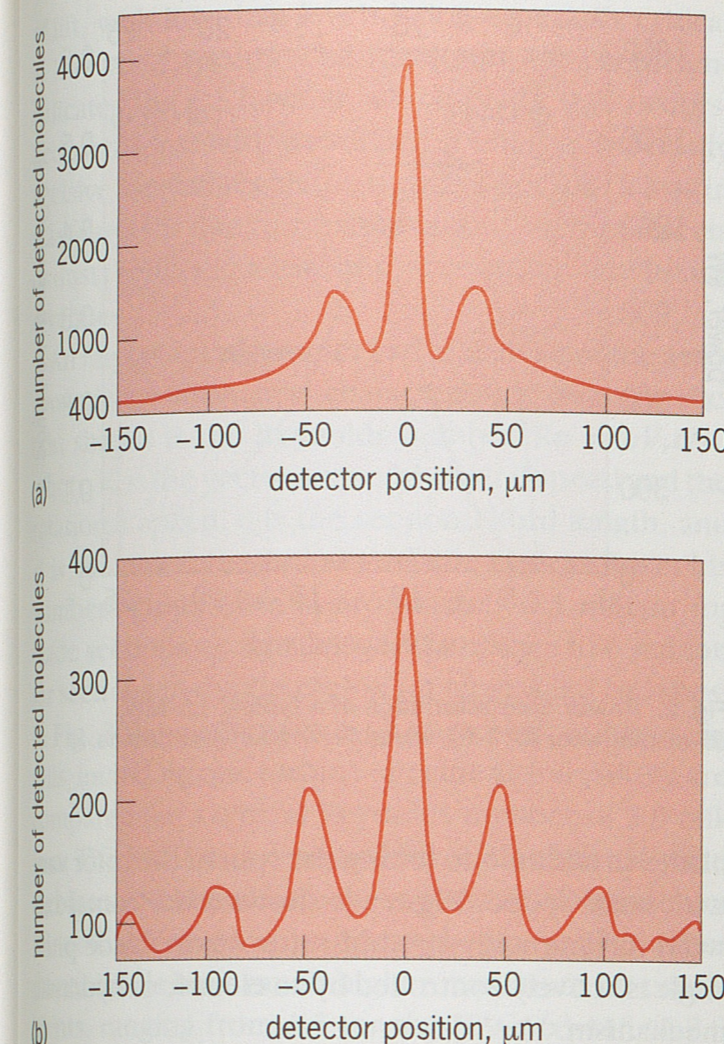


Fig. 3. Interference patterns of C_{60} molecules at a distance of 1.2 m (4 ft) after the 100-nm grating. (a) Interference pattern of molecules that have a full thermal velocity distribution. Besides the central peak, one interference minimum and one maximum can be seen on each side. The minimum is due to destructive interference of waves passing through neighboring slits. The first maximum on each side is due to constructive interference. (b) Interference pattern under similar conditions but with velocity selection (wavelength, $\lambda \sim 5$ pm, $\Delta\lambda/\lambda \sim 0.16$).

by applying the criterion that interference will be observed if there is no information about the path taken by the particle. Indeed, the emitted photons are expected to have a wavelength of a few micrometers, which is much larger than the spatial separation of the interfering paths through the diffraction grating, which amounts to 100 nm. Under these circumstances no optical instrument can resolve the path separation, which means that the photons carry no useful path information and the interference pattern can still persist. Only if very many long-wavelength photons were emitted, or a few photons of much shorter wavelength, would sufficient path information be carried into the environment and result in a destruction of the interference pattern.

While Fig. 3a still is of limited contrast due to the large velocity spread, a narrow velocity class was selected in a more recent experiment. As expected, almost perfect interference contrast was observed (Fig. 3b).

Further experiments. Future experiments will have to focus on various points. It will be interesting to investigate the possibility of destroying the interference pattern through a controlled coupling with the environment. This could be done either by heating the fullerenes up a great deal or by building an interferometer where the interfering beam paths are sep-

arated on a scale comparable with the wavelength of the emitted photons. The transition between quantum and quasi-classical physics could then be studied in detail. Another interesting direction of research would be to extend the techniques to the study of interference of biological macromolecules. It seems to be possible to develop methods which are scalable in mass. Thus one could investigate experimentally whether there are any fundamental obstacles for the observation of quantum interference of massive and complex mesoscopic objects. While it is not expected that any fundamental limits will be encountered, further investigations of quantum phenomena in the mesoscopic domain will certainly push forward the frontiers of current knowledge and also of coherent manipulation technologies.

For background information see COHERENCE; FULLERENE; INTERFERENCE OF WAVES; NONRELATIVISTIC QUANTUM THEORY; QUANTUM MECHANICS; QUANTUM THEORY OF MEASUREMENT; UNCERTAINTY PRINCIPLE in the McGraw-Hill Encyclopedia of Science & Technology.

Markus Arndt; Olaf Nairz; Anton Zeilinger
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Wind turbines

Over the centuries windmills and wind turbines have been used to grind grain, pump water, and generate electricity. The earliest windmill design on record dates back to the tenth century in West or Central Asia, where vertical-axis windmills were used for grinding corn. Windmills were primarily used for milling and pumping until 1888, when Charles F. Brush, an inventor and manufacturer of electrical equipment in the United States, designed and built the first windmill for the generation of electricity. For over 20 years his 12-kW horizontal-axis windmill was used to charge batteries for lights on his estate in Cleveland, Ohio. It took another century of developments in structural, aerodynamic, and electrical science and engineering to progress from the massive Brush windmill with its multiblade rotor to the sleek two- and three-bladed megawatt wind turbines of today. It was not until the last part of the twentieth century that a resurgence of interest in wind power sparked by the energy crisis and government tax incentives led to the development of relatively simple but efficient wind turbines and the first wind plants in California. After a bumpy start in the 1980s, the worldwide capacity of installed wind power grew rapidly to 12,455 MW at the end of 1999, with 20% (2490 MW) of this wind power residing in the United

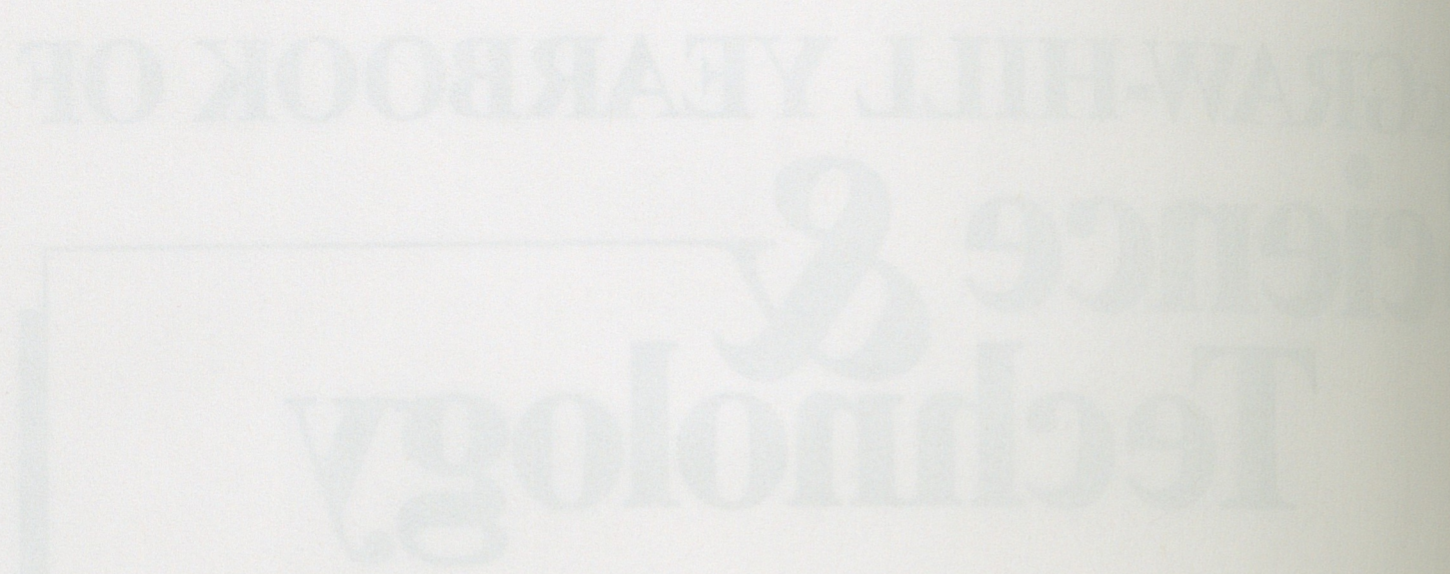
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