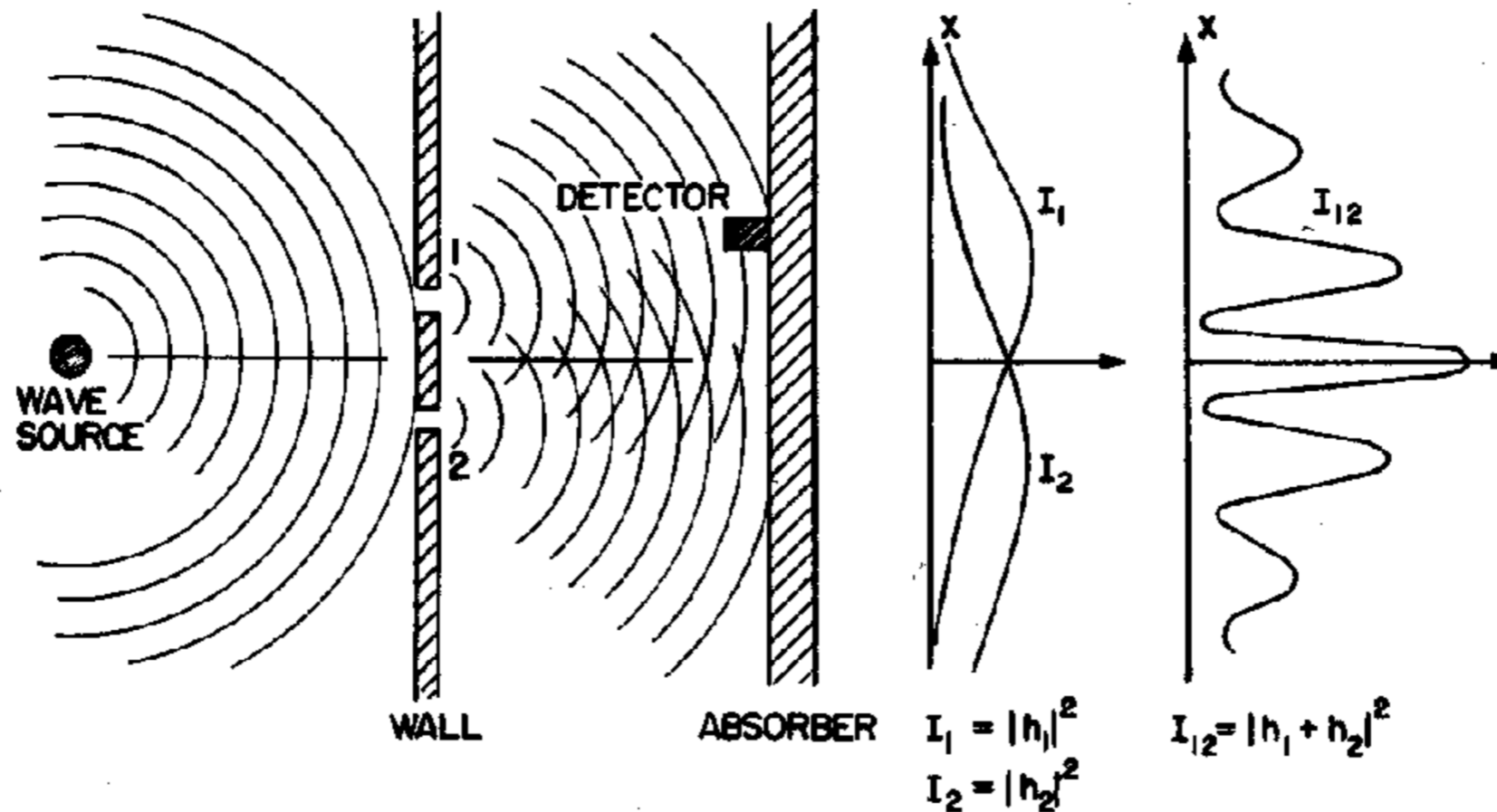


Decoherence in QM

M. Gold

updated Feb. 2020

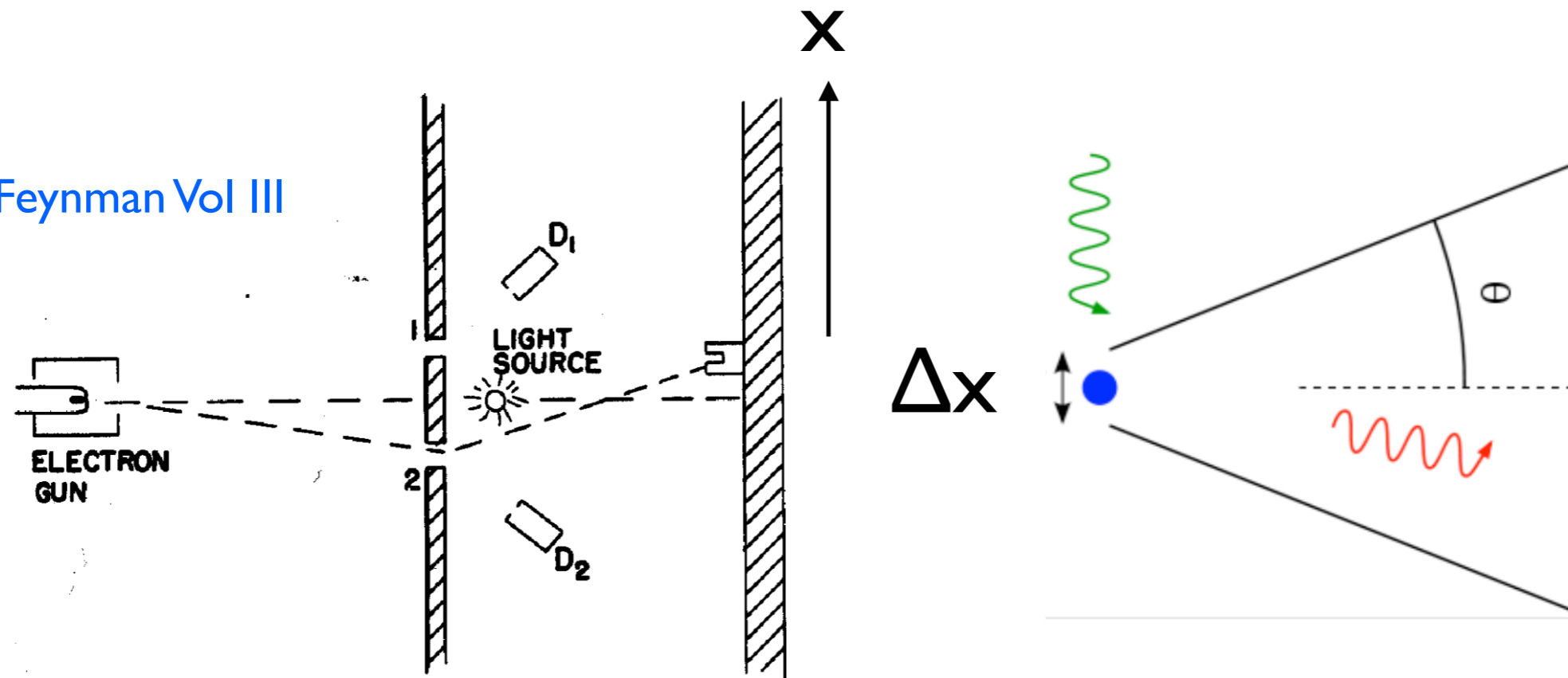
diffraction experiment



“In reality, it contains the only mystery, the basic peculiarities of all of quantum mechanics.” R. P. Feynman and A. R. Hibbs, Quantum Mechanics and Path Integrals McGraw-Hill, New York, 1965.

Heisenberg's Microscope

from Feynman Vol III



which slit determination destroys interference

$$\Delta p_x \sim h/\Delta x$$

Feynman emphasizes that decoherence occurs whether or not you detect the scattered photons

Quantum interference experiments with large molecules

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Am. J. Phys., Vol. 71, No. 4, April 2003 Nairz, Arndt, and Zeilinger #

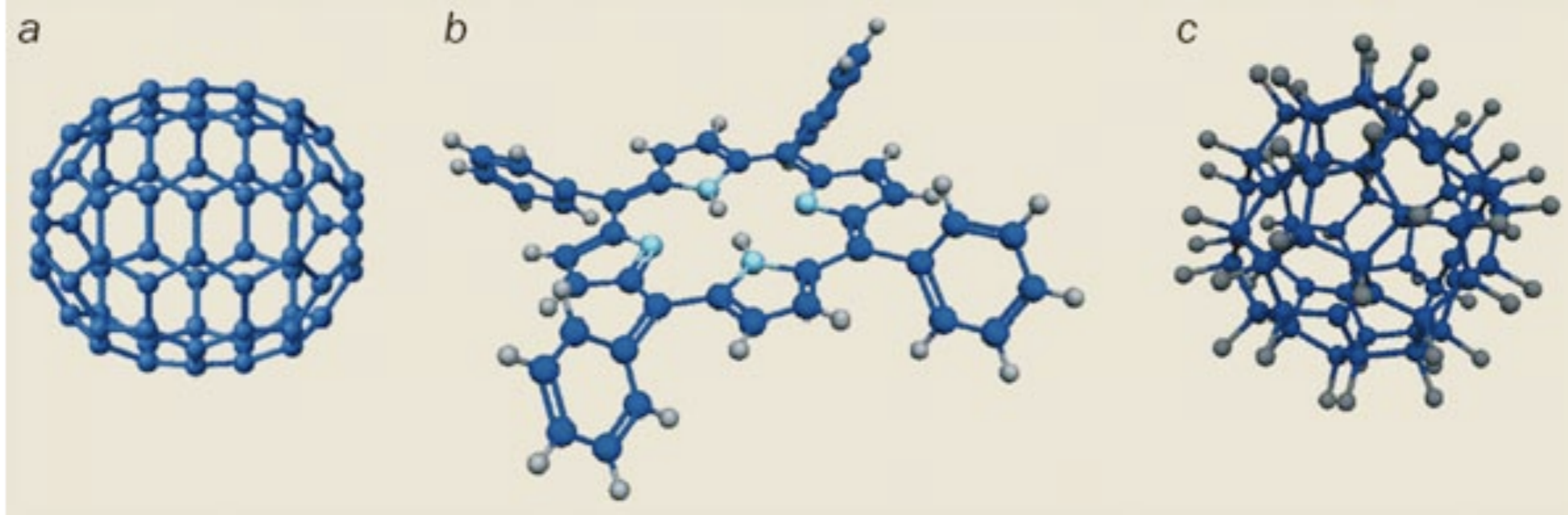


Fig. 2. The fullerene molecule C_{60} , consisting of 60 carbon atoms arranged in a truncated icosahedral shape, is the smallest known natural soccer ball.

see earlier work, PRL VOLUME 88, NUMBER 10 MARCH 11 2002

http://panda3.phys.unm.edu/nmcpp/gold/phys491/PhysRevLett_88_100404.pdf

2. WAVES OF MOLECULES



Physicists in the authors' group at Vienna have managed to observe interference using a range of molecules. These include (a) the buckyball carbon-70; (b) the pancake-shaped biomolecule tetraphenylporphyrin (TPP) $C_{44}H_{30}N_4$; and (c) the fluorinated fullerene $C_{60}F_{48}$. TPP is the first-ever biomolecule to show its wave nature. $C_{60}F_{48}$ has an atomic mass of 1632 units and currently holds the world record for the most massive and complex molecule to show interference.

900 K

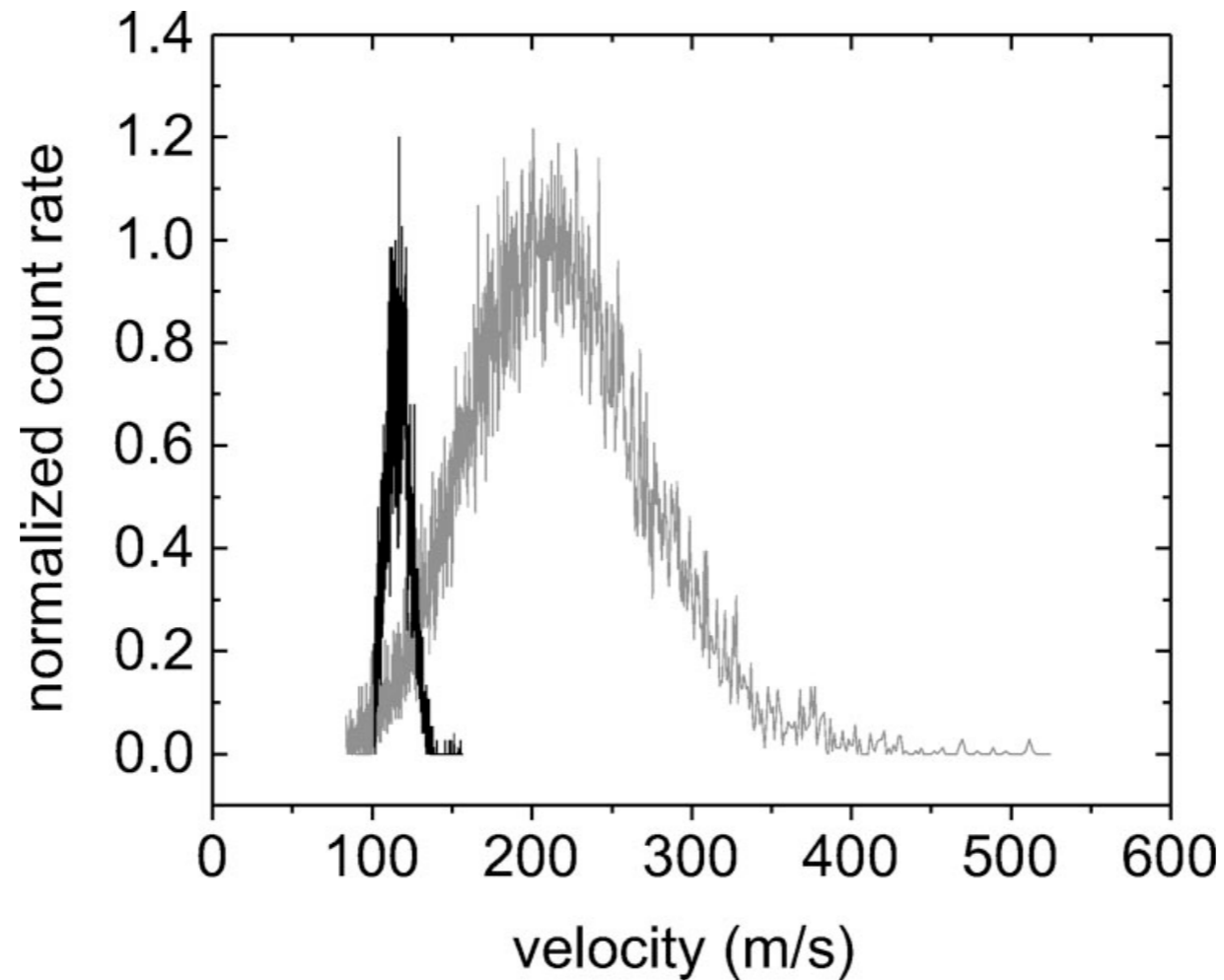


Fig. 5. Velocity distribution of the C_{60} molecules for a thermal and a velocity selected beam. The thermal beam (gray curve) is centered around $\bar{v} = 200$ m/s and has a width of $\Delta v/v \sim 0.6$, while the selected beam (black curve) is centered around $\bar{v} = 117$ m/s with a width of $\Delta v/v \sim 0.17$. We therefore expect the velocity selected interference pattern to be expanded by 70% on the screen and to show at least three times ($\approx 0.6/0.17$) as many interference orders as the unselected pattern.

Now they use a 100nm grating

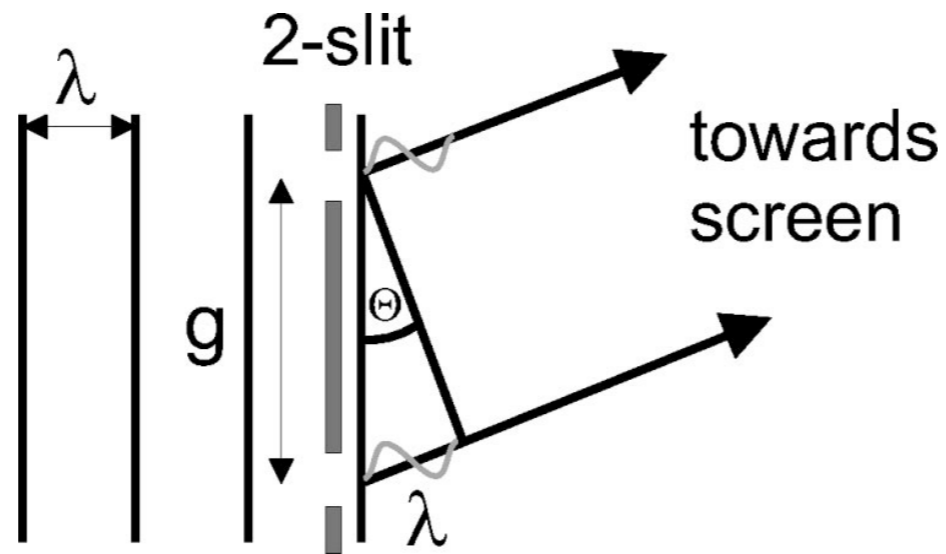
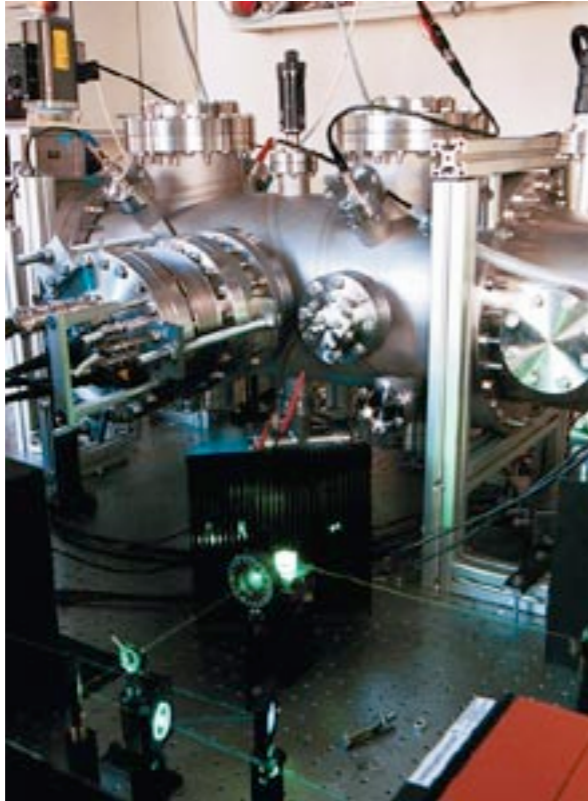


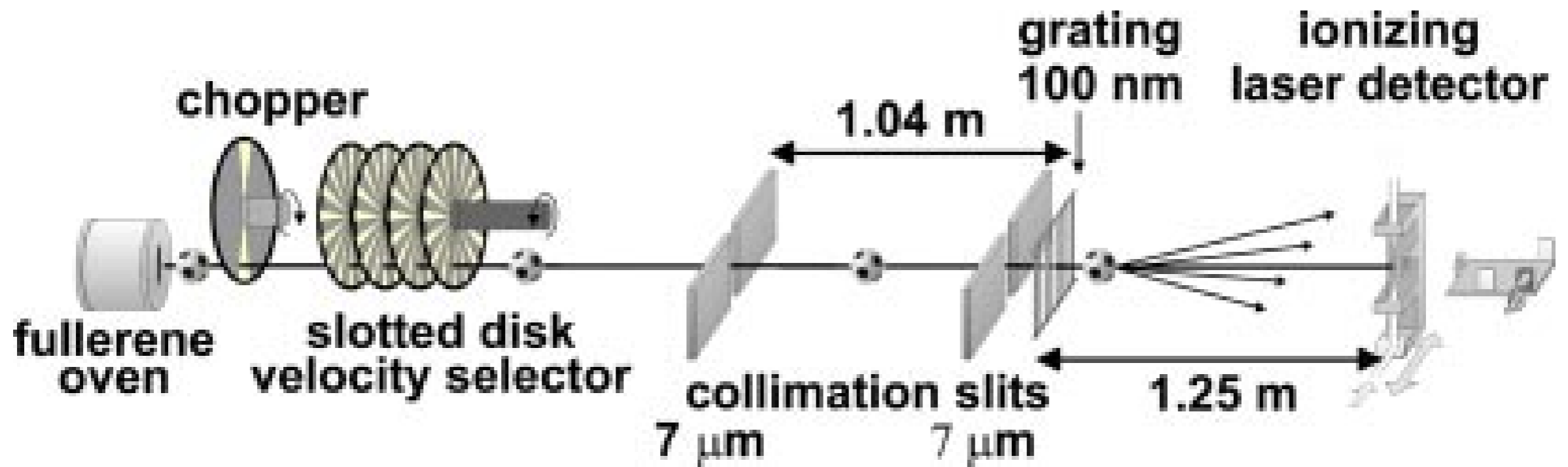
Fig. 4. Textbook approach to double-slit diffraction. First-order interference maxima of a monochromatic wave are caused by constructive interference of the wavelets that emerge from two neighboring slits. The corresponding path length difference between the two paths is equal to the de Broglie wavelength. Higher order interference will be spoiled by the limited longitudinal coherence in a thermal source. Velocity selection in our experiments increases the longitudinal coherence length by more than a factor of 3 and therefore permits the observation of higher order interference fringes.

As the diffracting element we used a free-standing silicon nitride grating with a nominal grating constant of $d = 100$ nm, slit openings of $s = 55 \mp 5$ nm and thickness of only 200 nm along the beam trajectory.

$$\theta = \frac{\lambda}{d} = \frac{2.8 \times 10^{-12} \text{ m}}{10^{-7} \text{ m}} = 28 \text{ } \mu\text{rad}.$$



U. Vienna experiment



schematic

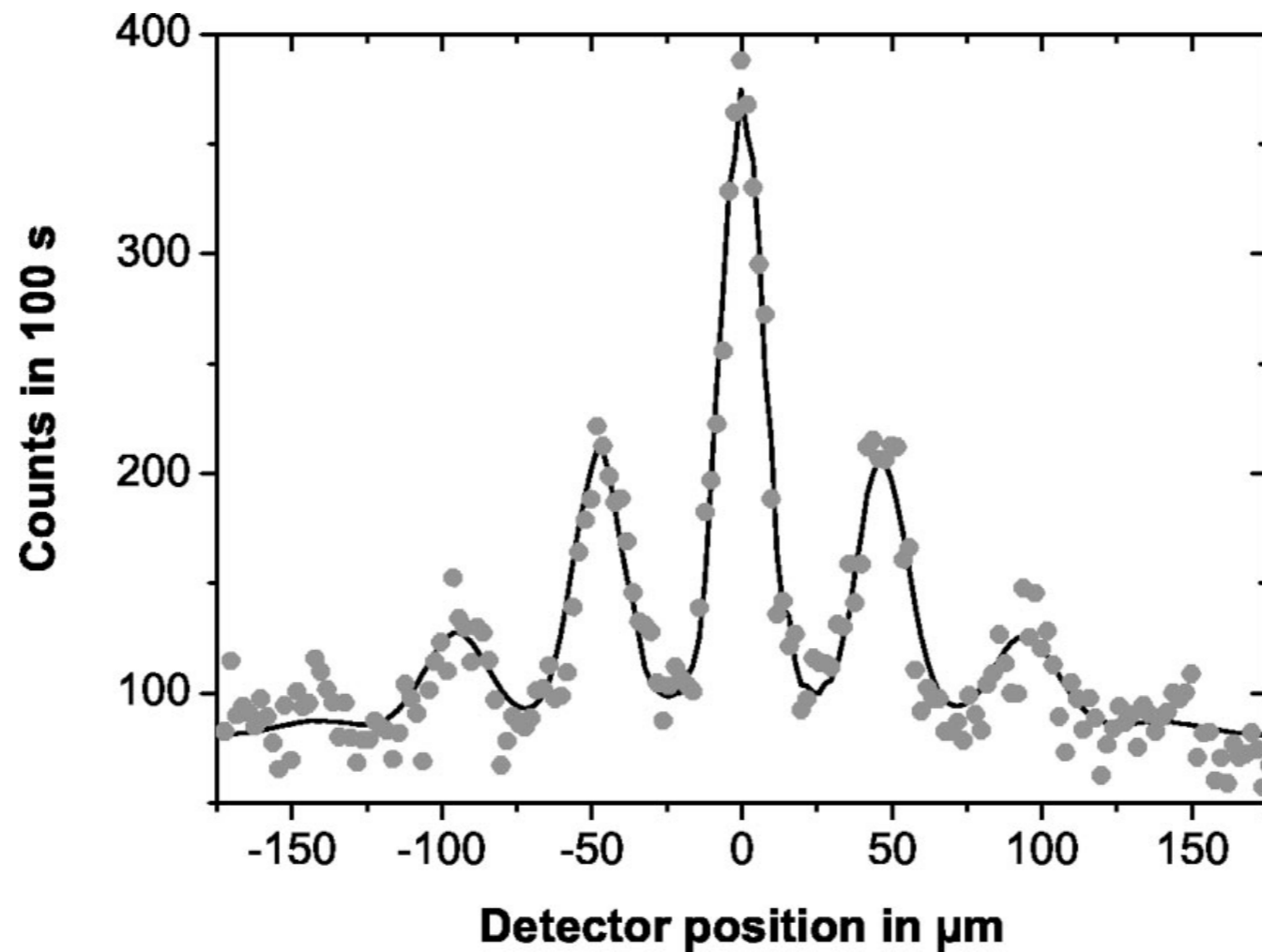


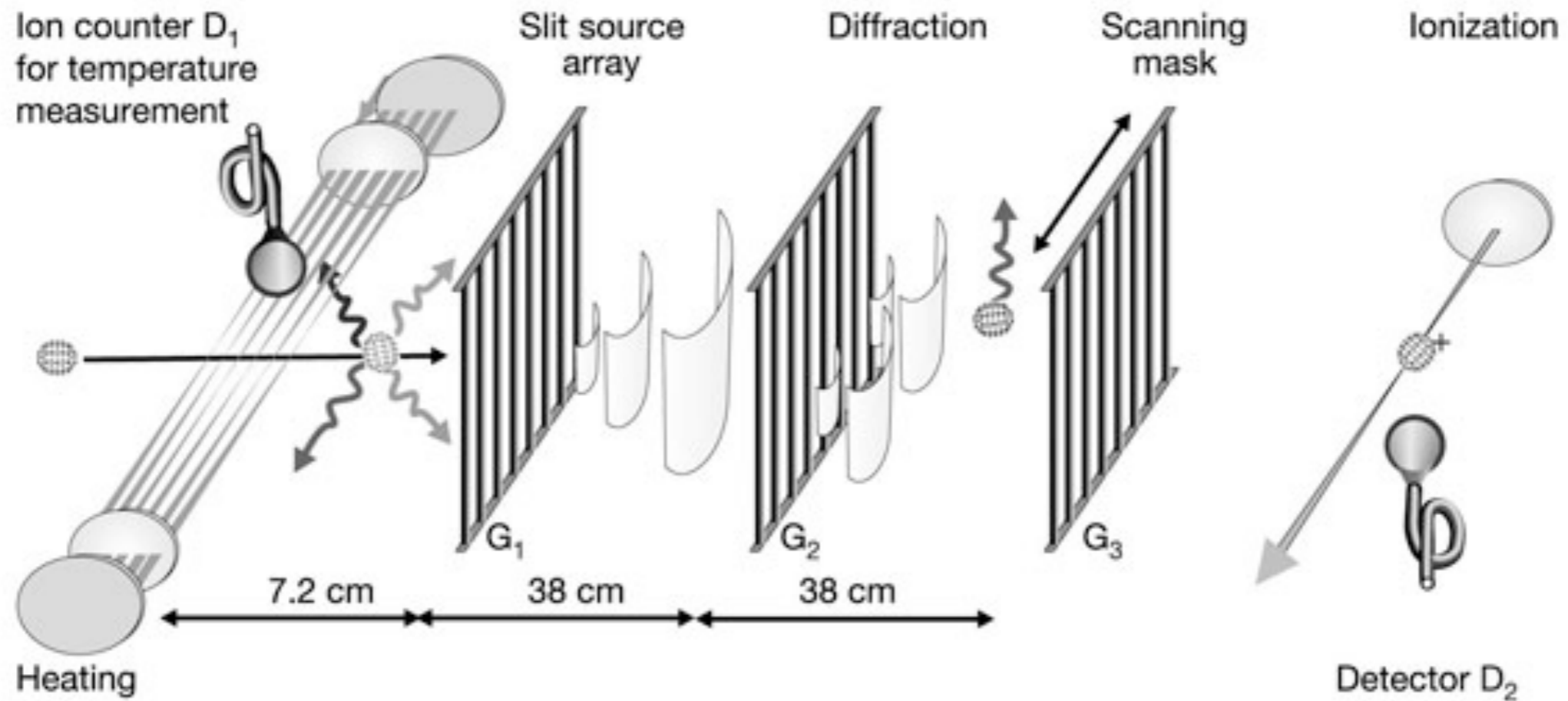
Fig. 7. Far-field diffraction of C_{60} using the slotted disk velocity selector. The mean velocity was $\bar{v} = 117$ m/s, and the width was $\Delta v/v \sim 17\%$. Full circles represent the experimental data. The full line is a numerical model based on Kirchhoff–Fresnel diffraction theory. The van der Waals interaction between the molecule and the grating wall is taken into account in form of a reduced slit width. Grating defects (holes) additionally contribute to the zeroth order.

Decoherence of matter waves by thermal emission of radiation

Lucia Hackermüller, Klaus Hornberger, Björn Brezger, Anton Zeilinger & Markus Arndt

Nature **427**, 711-714 (19 February 2004)

Large molecules are particularly suitable for the investigation of the **quantum–classical transition** because they can store much energy in numerous internal degrees of freedom; the internal energy can be converted into thermal radiation and thus induce decoherence. Here we report matter wave interferometer experiments in which C₇₀ molecules lose their quantum behaviour by thermal emission of radiation. We find good quantitative agreement between our experimental observations and microscopic decoherence theory. Decoherence by emission of thermal radiation is a general mechanism that should be relevant to all macroscopic bodies.



A fullerene beam passes from left to right, interacting with a heating stage, a three-grating (G₁–G₃) matter-wave interferometer and an ionizing detection laser beam in D₂ (wavelength 488 nm, 1/e² intensity radius 6.6 m, 15 W). The gold gratings have a period of 991 nm and slit widths of nominally 475 ± 20 nm. Decoherence of the fullerene matter waves can be induced by heating the molecules with multiple laser beams (514.5 nm, 40 m waist radius, 0–10 W) before they enter the interferometer. The resulting molecular temperature can be assessed by detecting the heating-dependent fraction of fullerene ions using the electron multiplier D₁ over the heating stage.

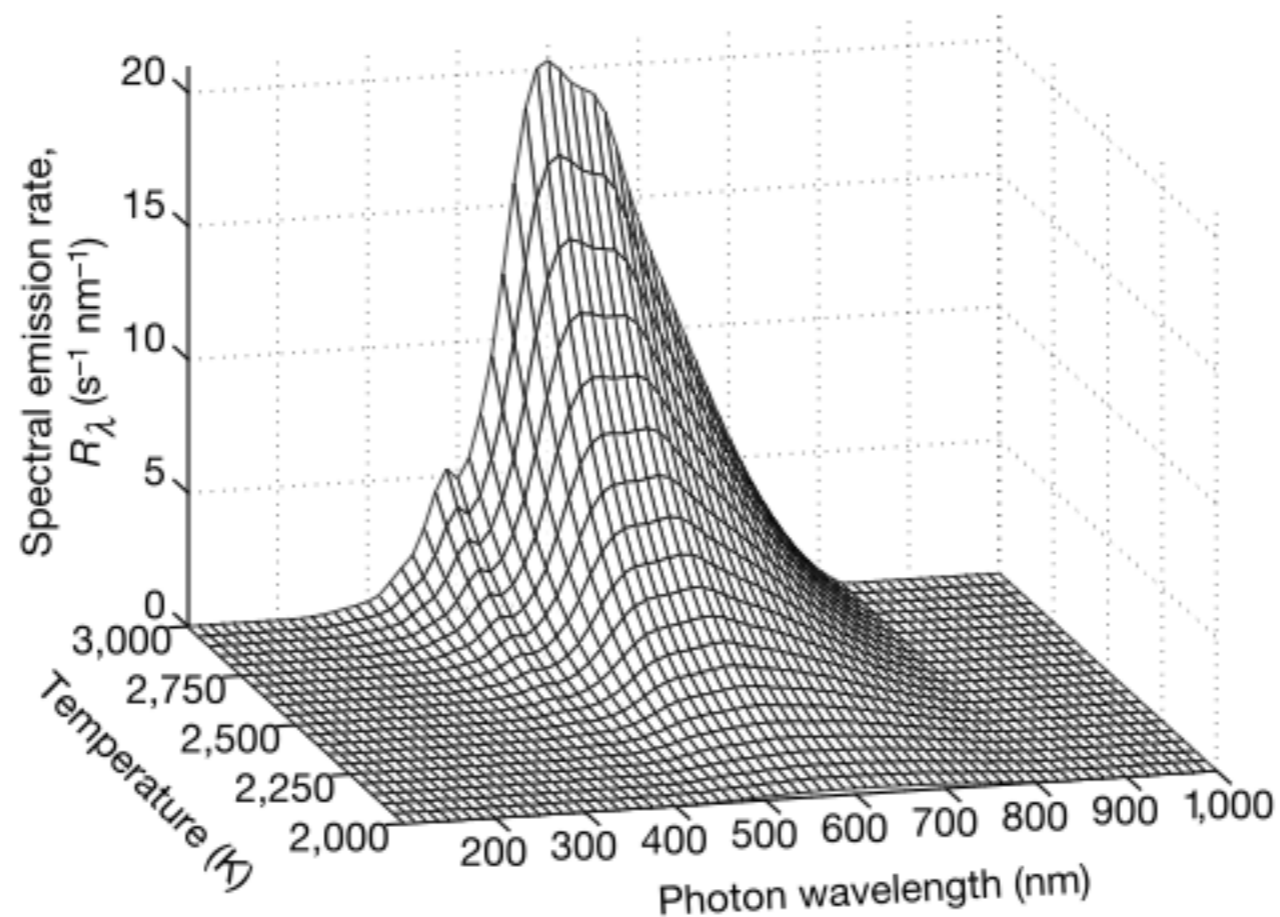
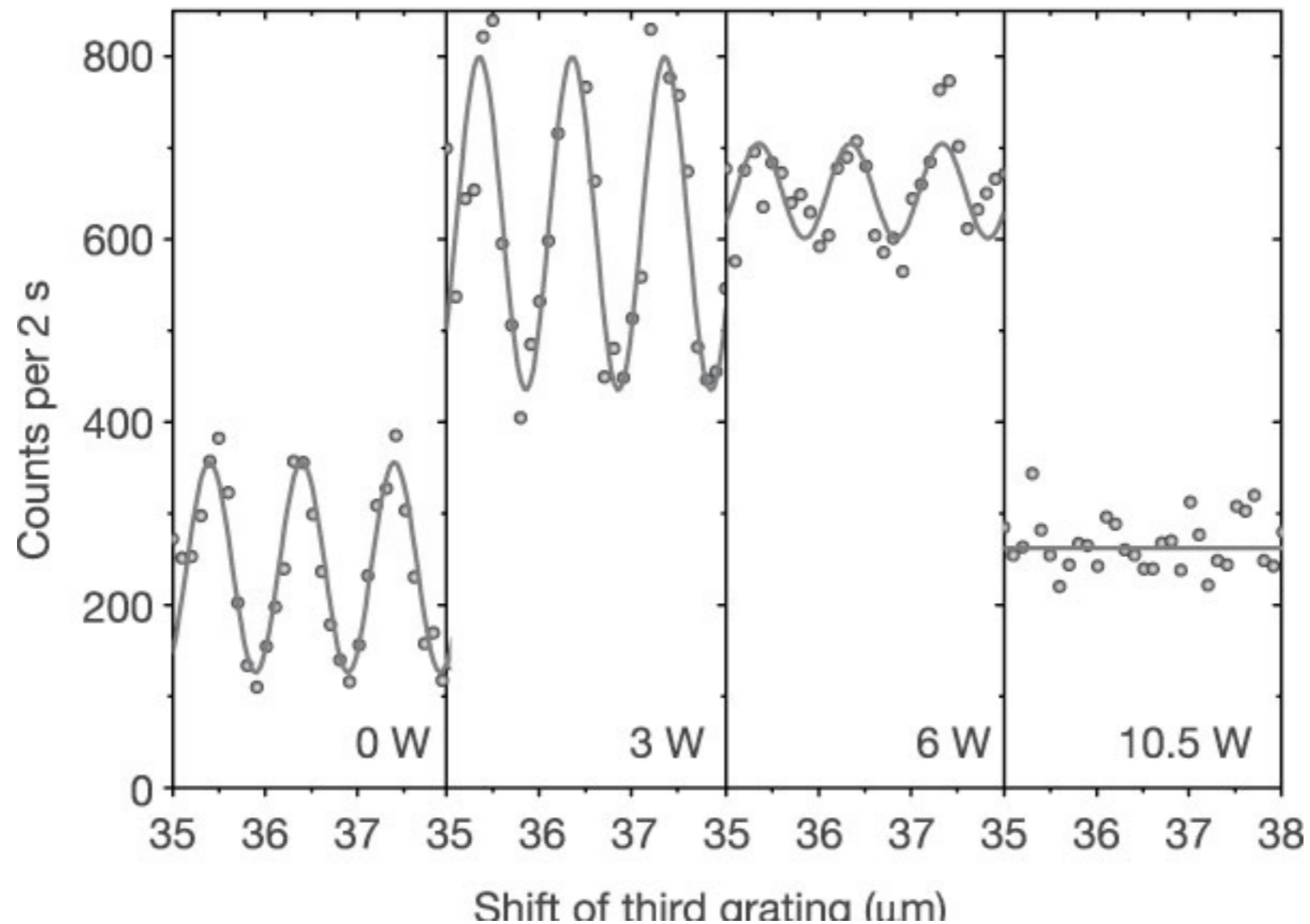
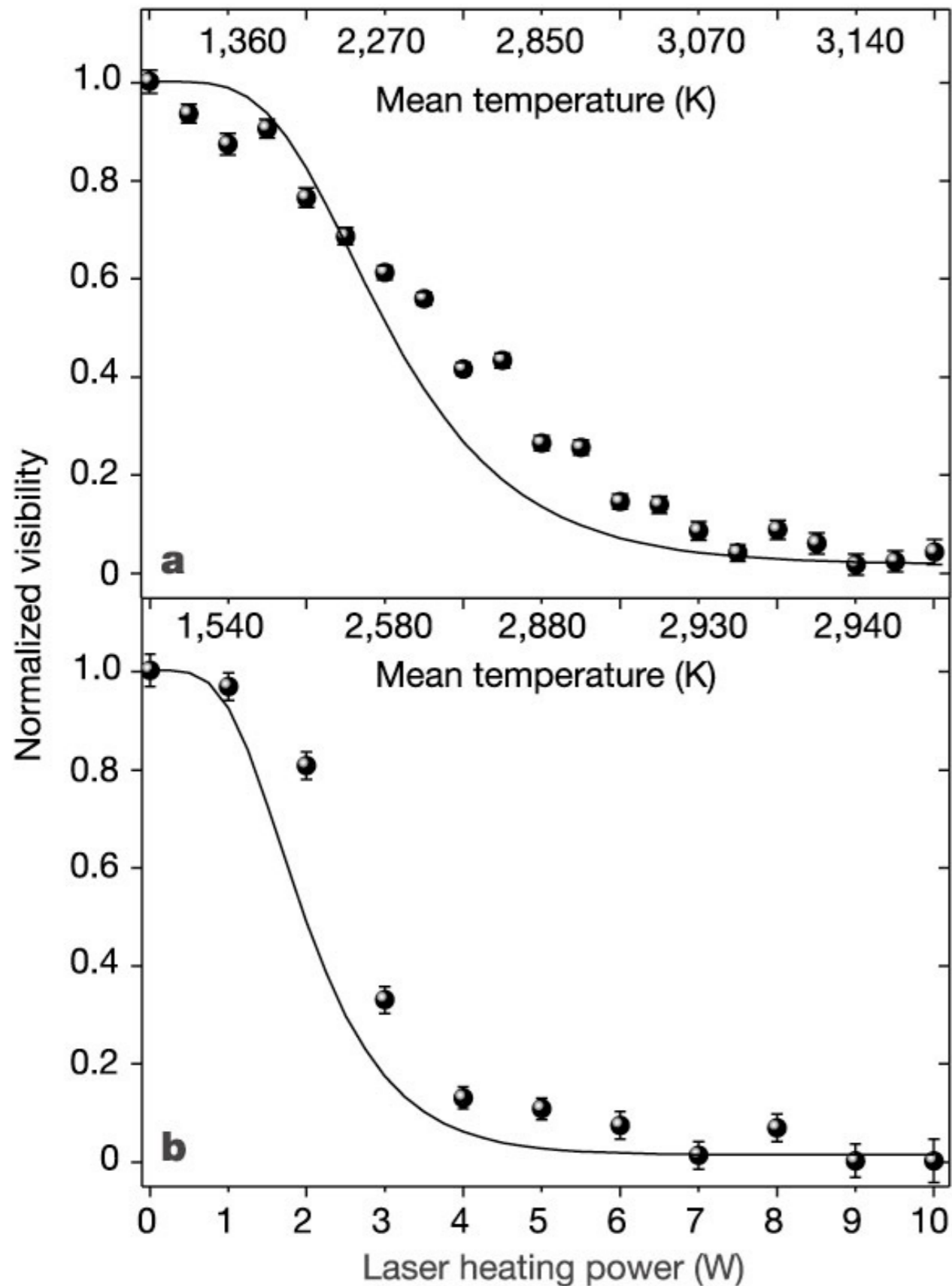


Figure 3 Spectral photon emission rate R_λ of C_{70} molecules, as used for the calculation of thermal decoherence. We use the published²⁵ absorption cross-section for ($S_0 \rightarrow S_1$) and a heat capacity of $C_V = 202 k_B$. The fall-off to short wavelengths is determined by the limited internal energy of the molecules, while the decrease at long wavelengths is due to the lack of accessible radiative transitions at energies below ~ 1.5 eV. The figure shows that in the absence of cooling a single molecule at 2,500 K travelling at 190 m s^{-1} (that is, with a transit time of 4 ms through the interferometer) would emit an integrated number of three visible photons. This is sufficient to determine the path of the molecule if the emission occurs close to the second grating.



The fringe visibility V decreases with increasing heating power P owing to the rising emission probability of visible photons: $P = 0 \text{ W}$ ($V = 47\%$), $P = 3 \text{ W}$ ($V = 29\%$), $P = 6 \text{ W}$ ($V = 7\%$), $P = 10.5 \text{ W}$ ($V = 0\%$). In contrast to that, the absolute count rate grows initially with increasing P . This is due to the fact that the thermal ionization probability in detector D_2 increases with the temperature of the arriving molecules. At even higher heating intensities the count rate falls again because of ionization and fragmentation in the heating stage.



a, Interference visibility as a function of laser heating power (lower scale). The molecular beam with a mean velocity of $v_m = 190 \text{ m s}^{-1}$ passes a 50 m central height delimiter comparable to the waist (40 m) of the 16 heating laser beams. We observe a rapid decrease of the fringe visibility with increasing power both in the experiment (circles) and in theory (solid line). The upper axis indicates the mean temperature of the molecules when they enter the interferometer. The maximum contrast without heating was $V_0 = 47\%$, which is close to the theoretical value¹¹.

b, Molecules with $v_m = 100 \text{ m s}^{-1}$, selected by a 150 m height delimiter and heated by ten beams of the specified incident laser power. The qualitative behaviour is the same and the quantitative agreement with theory is as good as before. The maximum contrast for this velocity class was $V_0 = 19\%$. In both experimental arrangements, a mean number between one and two visible photons is required to reduce the contrast by a factor of two.

This experiment proves three things:

- 1) First, it shows that decoherence due to heat radiation can be quantitatively traced and understood.
- 2) Second, it confirms the view that decoherence is caused by the flow of information into the environment. In matter-wave interferometers, which only observe the centre-of-mass motion alone, information can only be mediated by a transfer of momentum.
- 3) Finally, it shows that thermal decoherence is relevant for truly macroscopic objects. Fortunately, it will be less of a concern in future interferometry experiments with large molecules, clusters or nano-crystals. Objects like these will have to be substantially cooled to make them coherent and to suppress the emission of thermal radiation.