Quantum interference experiments with large molecules

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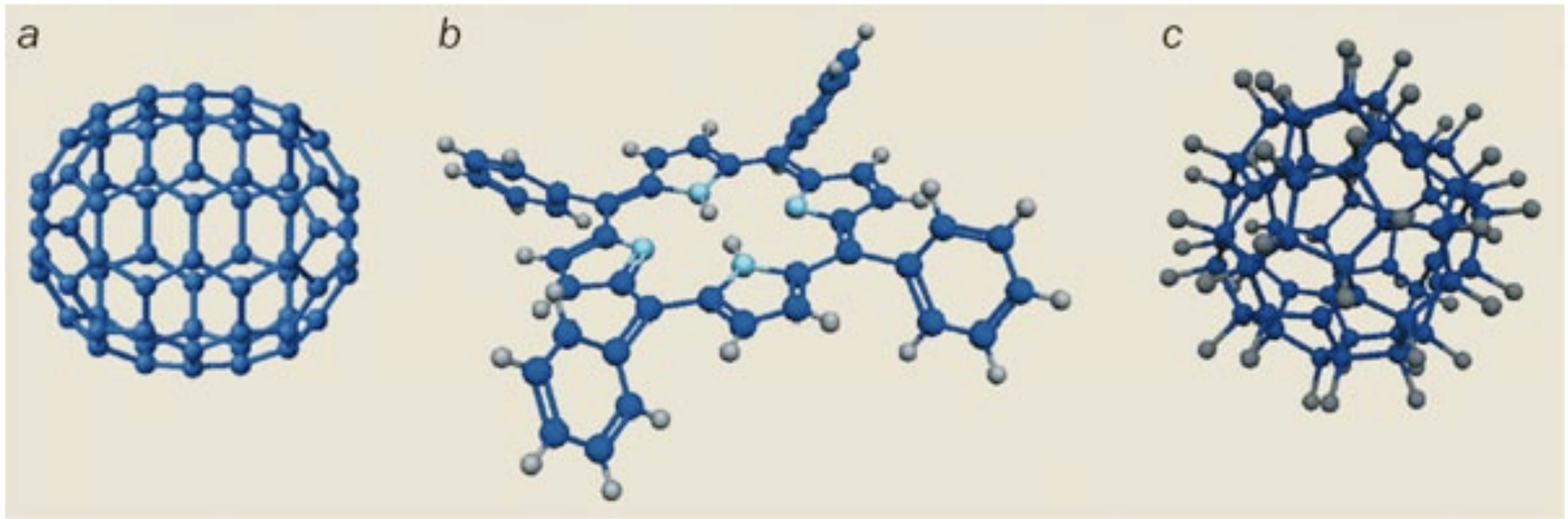
Am. J. Phys., Vol. 71, No. 4, April 2003 Nairz, Arndt, and Zeilinger #

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.

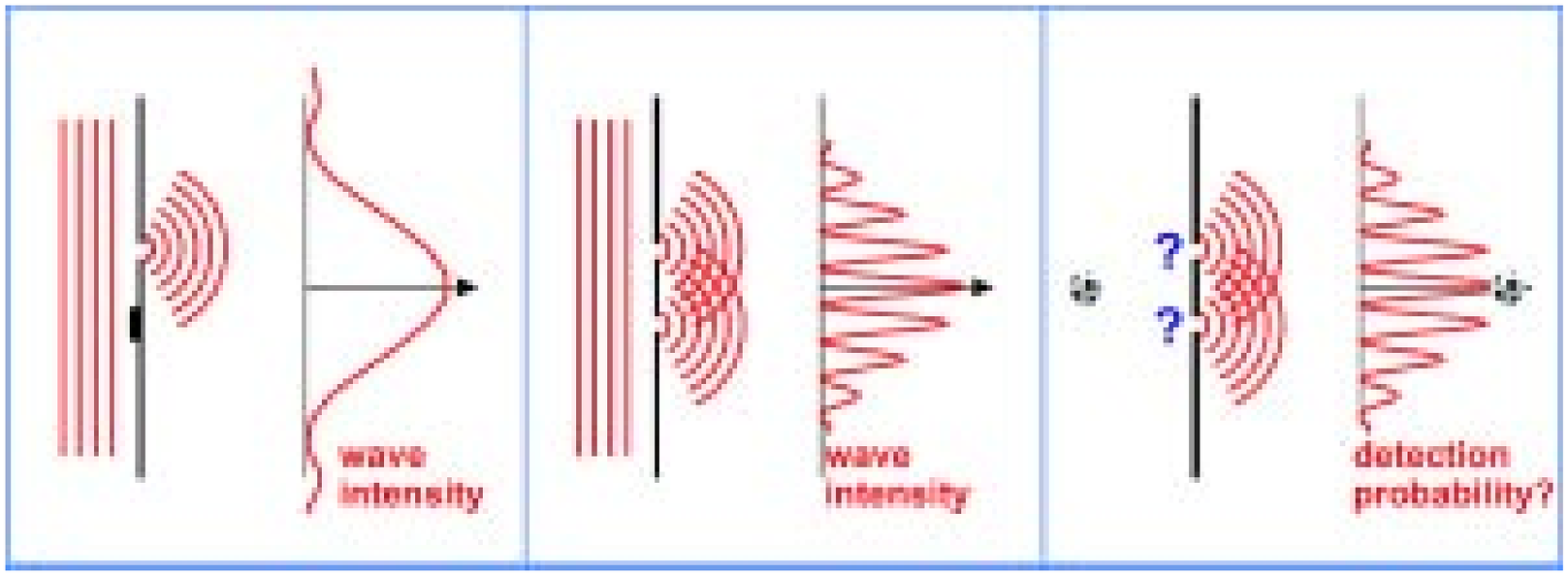
see earlier work, PRL VOLUME 88, NUMBER 10 MARCH 11 2002

2. WAVES OF MOLECULES



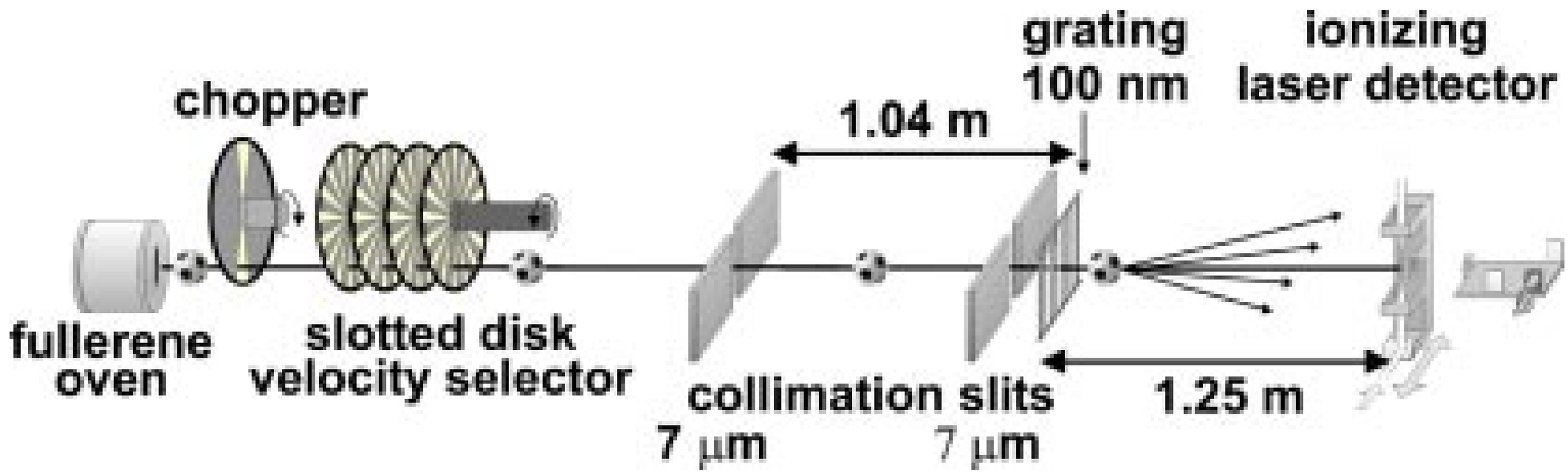
Physicists in the authors' group at Vienna have managed to observe interference using a range of molecules. These include *(a)* the buckyball carbon-70; *(b)* the pancake-shaped biomolecule tetraphenylporphyrin (TPP) $C_{44}H_{30}N_4$; and *(c)* the fluorinated fullerene $C_{60}F_{48}$. TPP is the first-ever 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.

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.

U.Vienna experiment



schematic

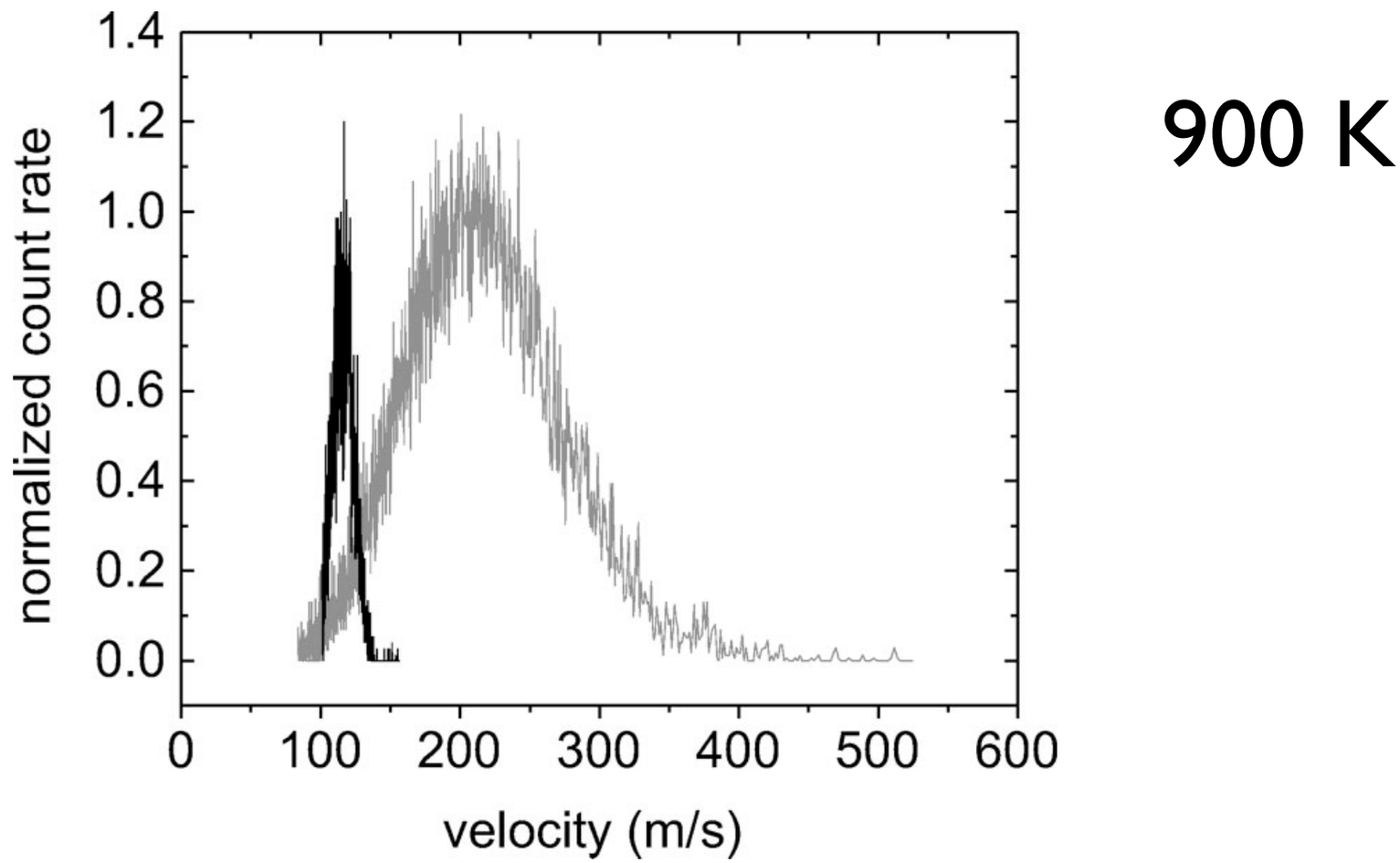


Fig. 5. Velocity distribution of the C_{60} molecules for a thermal and a velocity selected beam. The thermal beam (gray curve) is centered around $\bar{v} = 200$ m/s and has a width of $\Delta v/v \sim 0.6$, while the selected beam (black curve) is centered around $\bar{v} = 117$ m/s with a width of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

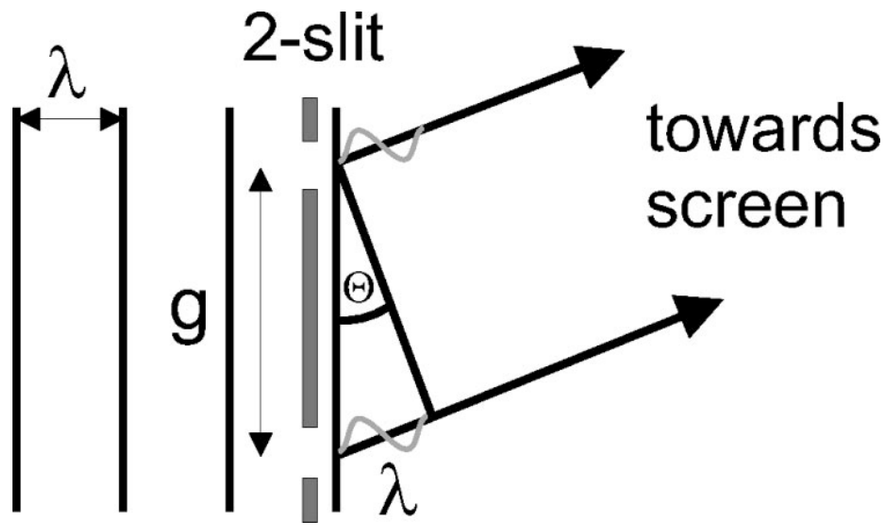


Fig. 4. Textbook approach to double-slit diffraction. First-order interference maxima of a monochromatic wave are caused by constructive interference of the wavelets that emerge from two neighboring slits. The corresponding path length difference between the two paths is equal to the de Broglie wavelength. 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.

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

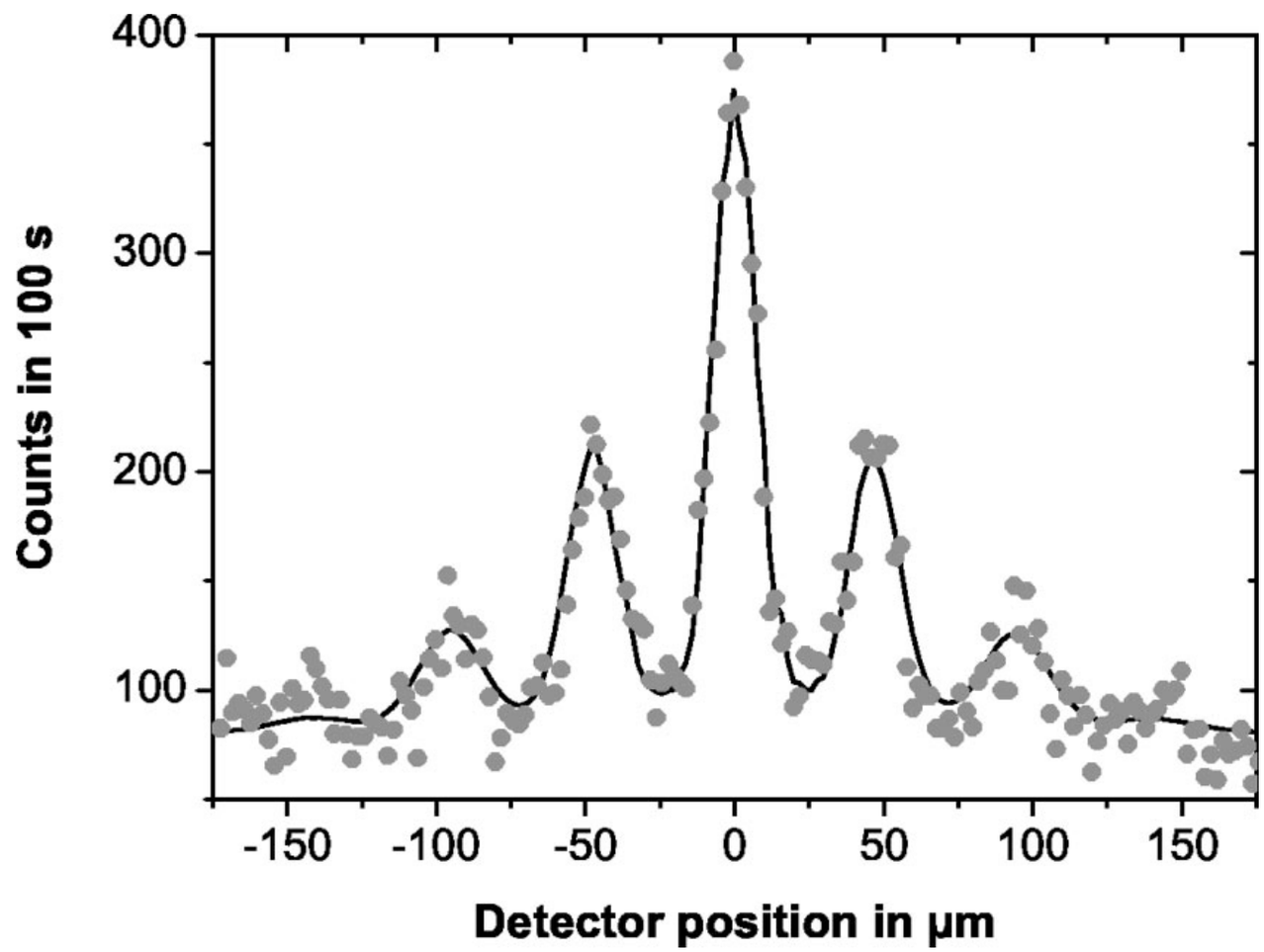


Fig. 7. Far-field diffraction of C_{60} using the slotted disk velocity selector. The mean velocity was $\bar{v} = 117$ m/s, and the width was $\Delta v/v \sim 17\%$. Full circles represent the experimental data. The full line is a numerical model based on Kirchhoff–Fresnel diffraction theory. The van 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

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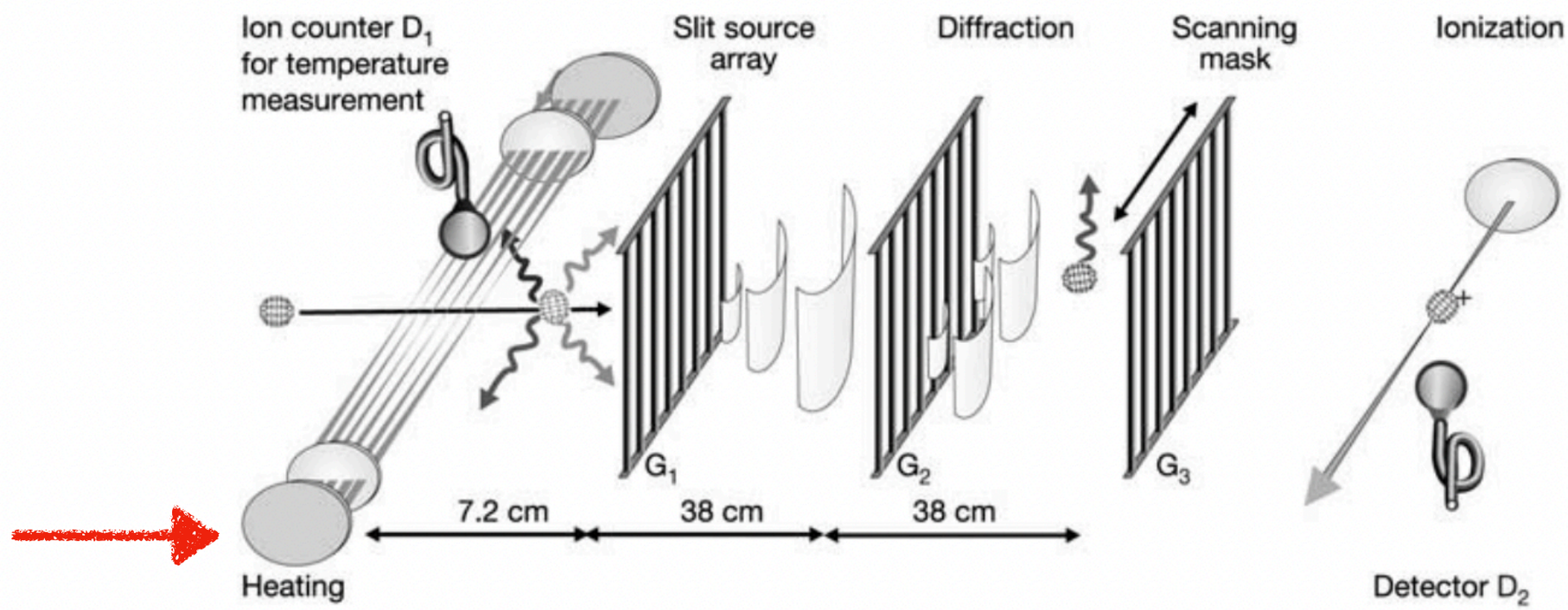
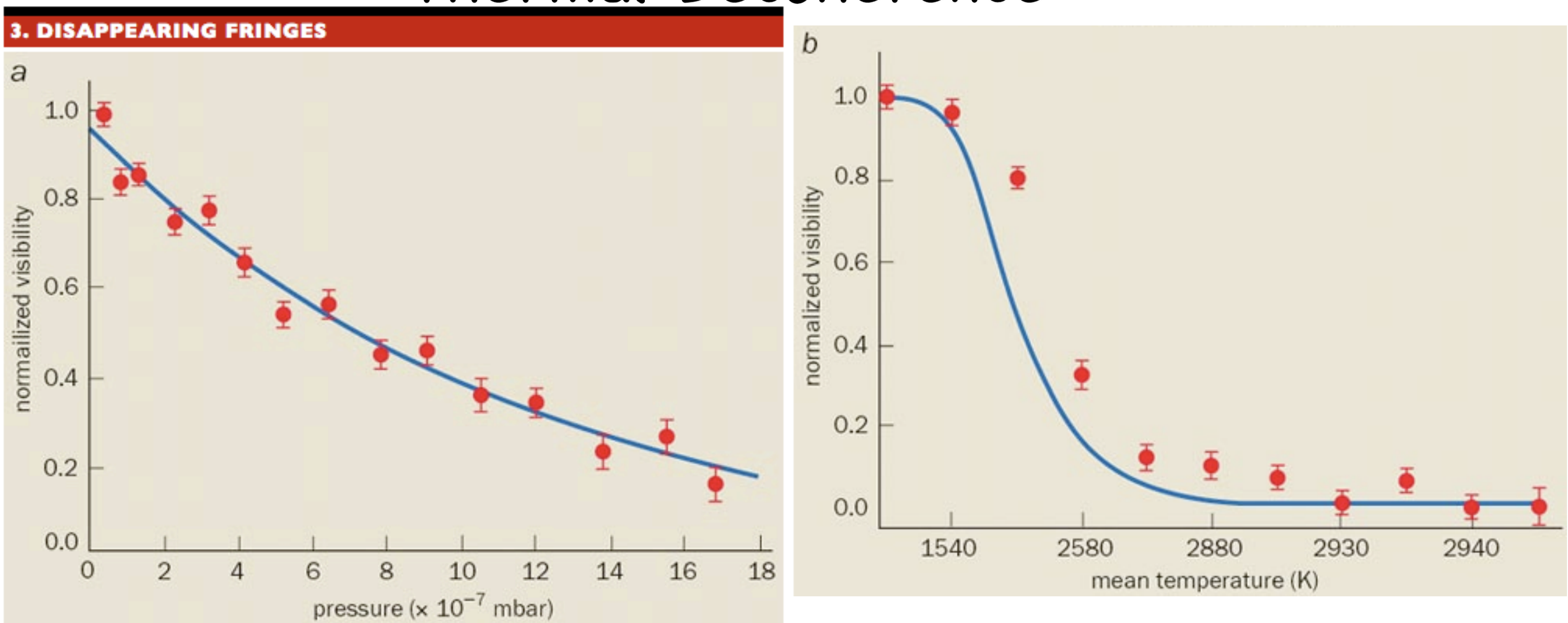


Figure 1 Set-up for the observation of thermal decoherence in a Talbot–Lau molecule interferometer. A fullerene beam passes from left to right, interacting with a heating stage, a three-grating (G_1–G_3) matter-wave interferometer and an ionizing detection laser beam in D_2 (wavelength 488 nm, $1/e^2$ intensity radius 6.6 μm, 15 W). The gold gratings have a period of 991 nm and slit widths of nominally 475 $\pm$ 20 nm. Decoherence of the fullerene matter waves can be induced by heating the molecules with multiple laser beams (514.5 nm, 40 μm waist radius, 0–10 W) before they enter the interferometer. Th resulting molecular temperature can be assessed by detecting the heating-depen fraction of fullerene ions using the electron multiplier D_1 over the heating stage.

Thermal Decoherence



Molecules that interact with their environment by colliding with other gas molecules or emitting thermal radiation can no longer create interference patterns. They lose their quantum behavior because information about the molecules is now, in principle, available - even if an observer does not actually extract that information. These graphs show the loss of interference with carbon-70 molecules in a Talbot-Lau interferometer in terms of the "normalized visibility", which is a measure of the contrast between light and dark bands of the interference pattern. (a) If gas is added to the interferometer, the visibility drops exponentially as the gas pressure increases. (b) If the molecules are heated by a laser of increasing power, they get hotter and emit more photons, which causes the relative visibility to fall slowly but nonlinearly. The entanglement with the environment is mediated via the colliding molecules and thermally emitted photons, respectively.

This experiment proves three things.

- First, it shows that decoherence due to heat radiation can be quantitatively traced and understood.

- 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.

- 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 nanocrystals. Objects like these will have to be substantially cooled to make them coherent and to suppress the emission of thermal radiation.