Optical traps: general applications

- hold and move
  - macroscopic dielectric objects (particles up to ~10\(\mu\)m diameter)
  - microscopic dielectric objects (trapping molecules, lasercooling of atoms)

- measure forces on trapped particles
  - learn something about molecule - molecule interaction
    (e.g. molecular motors)
The idea: radiation pressure

- first developed by A. Ashkin in 1970
- force on every object reflecting/scattering or refracting light
- negligible for ordinary objects (e.g. 60W light on optimal mirror: $F \sim 10^{-7}$ N)
- significant for particles < 1µg

![Conservation of momentum diagram]

100% reflecting mirror

incoming radiation: momentum $P$

conservation of momentum: $2P$
Force on polystyrene bead (homogenous intensity)

- particle diameter > wavelength: ray optics picture sufficient to calculate forces
- ray $a$ equal to ray $b$ $\implies |F_a| = |F_b|$
- resultant force $F_{scat}$ along optical axis due to scattering effects on surface
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**Force on polystyrene bead (gaussian intensity profile)**

- $n_{\text{bead}} > n_{\text{medium}}$, bead's light transmission < 100%
- Ray a: higher intensity than ray b $\implies |F_a| > |F_b|$
- Resultant transversal force $F_{\text{grad}}$ to beam center (maximum of intensity)
- But $F_{\text{scat}}$ still along optical axis due to scattering effects on surface
One of Ashkin's first experiments

- bead is pulled to intensity maximum and pushed forward
- verification of theoretical predictions
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Focused laserbeam: specify longitudinal force

- bead not in focus: resultant refraction force to focus
- light coming from edges of objective contributes most to this force
- high numerical aperture (NA) needed for high longitudinal refraction force.
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Single-beam Tweezer

transversal stabilisation due to intensity gradient (gaussian profile)

longitudinal stabilisation due to intensity gradient (strong focused laser)

balance out longitudinal refraction- and scatteringforce: trapped particle

Jan-Philip Gehrcke
Single-beam OT: trapping force

- When does the bead leave the trap?
- for single-beam OTs: $F_{\text{trap}} \sim 60 \text{ pN}$
Single-beam OT: measuring forces on trapped particles

- theoretically simple technique to measure forces
- conservation of momentum: Force $F$ exerted by the laser is the difference between entering momentum flux and outgoing momentum flux
- momentum flux $Q = nW / c$ ($W$: power of light, $n$: refraction index of outer medium)
- to measure $Q_{\text{out}}$ all the outgoing rays have to be collected and detected
- therefore the back aperture of objective lens has to be underfilled

PROBLEM: very high NA needed for functionality of single-beam trap
Single-beam OT: trapping force problems

- small trapping force
- decreasing back aperture filling to enable force measurement also means decreasing the trapping force or even to disable the trap
- observation of intermolecular processes with forces higher than $F_{\text{trap}}$ is not possible
Solution: dual-beam optical trap

- two equal laser beams face each other and are focused in the same spot
- scattering forces cancel up
- after underfilling back apertures: resultant trapping force is still up to 200 pN and force measurements are possible (extremely precisely; with technique described before)
- trap is very stable (important for biological investigations)
Dual-beam optical trap: difficulties

- complexity (has to be constructed precisely from many single parts)
- alignment of optical paths (lasers exactly have to face each other)
- standard implementations of these instruments did not exist after 6 years of usage (2002)

if possible, a 'standard' single-beam tweezer is used
Experimental realisation
Applications in biophysics: examples
Applications in biophysics: molecular motors

measurement of 8 nm steps of kinesin against 5 pN force
Applications in biophysics: molecular motors

movement observation of RNA polymerase enzyme along DNA molecule

1998 Wang et al. found out, that RNA is a powerfull motor with a stall force of 21 - 27 pN in comparison to kinesin (a motor protein with a stall force of 5 - 7 pN) and (1995, Yin et al.) a speed > 10 nucleotids per second.
Applications in biophysics: micromechanical properties

Measurement of the stretching of double- and singlestranded DNA

- graph: transformation of dsDNA to ss DNA at ~ 70 pN
- 1997 Wang et al. could determine persistence length and elastic modulus of DNA. They observed a significant effect on DNA stiffness by ionic strength.
DUAL-BEAM OPTICAL TWEEZERS (TRAPS)

Literature

- Grange et al. (2002) Rev. Sci. Instr. 73, 2308 - 2316
- Marc C. Williams: *Optical Tweezers: Measuring Piconewton Forces*
- Kai Urig, Heike Böhm: *Praktikum Biophysikalische Chemie: Optische Pinzetten*, 2005