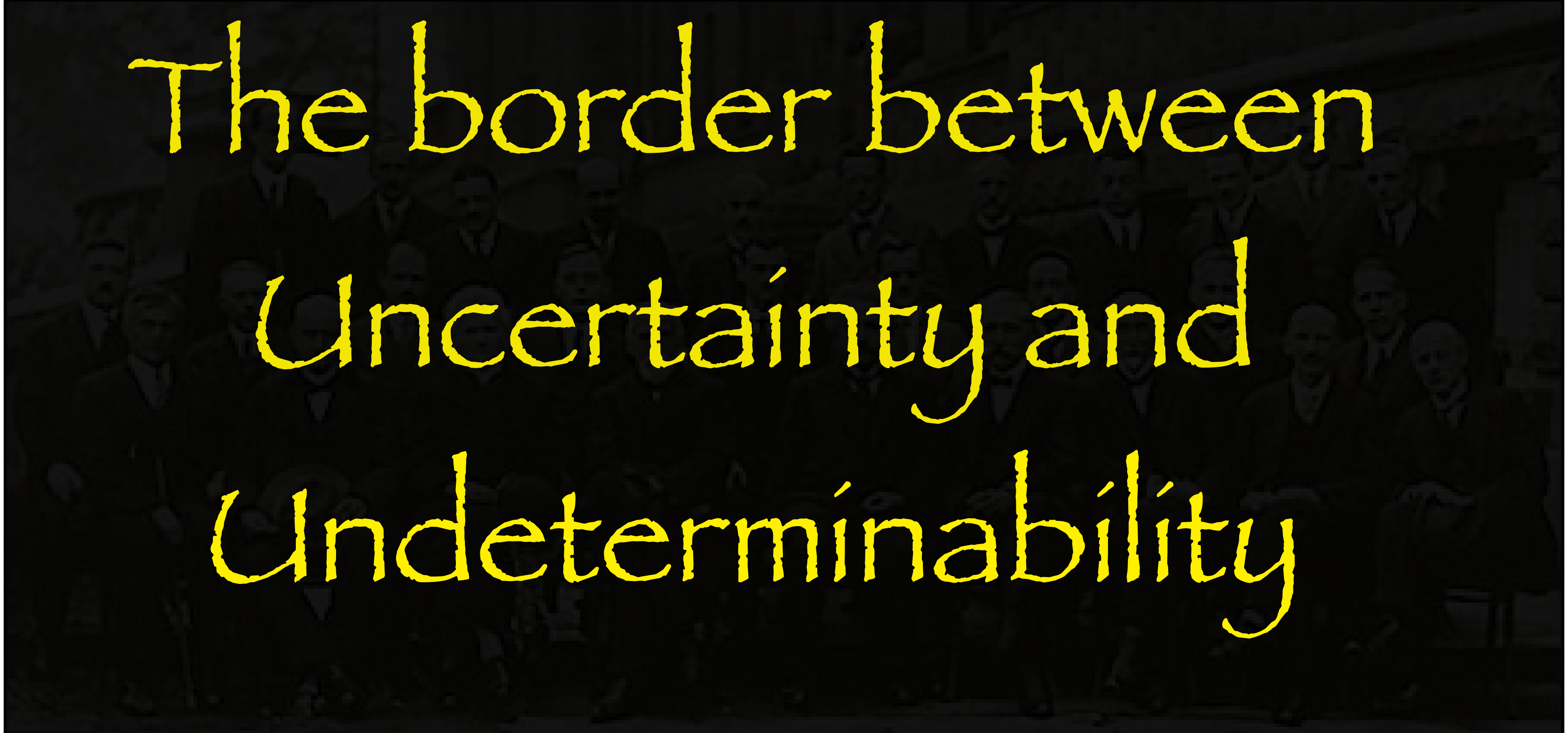


The border between Uncertainty and Undeterminability

Björgvin Hjörvarsson

Copenhagen interpretation

The wave-particle duality

Solvay conference 1927

Considerations.....

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

The quantum-mechanical description cannot simultaneously be complete and consistent. (fullständig och självkonsistent)

The answer.....

OCTOBER 15, 1935 PHYSICAL REVIEW VOLUME 48

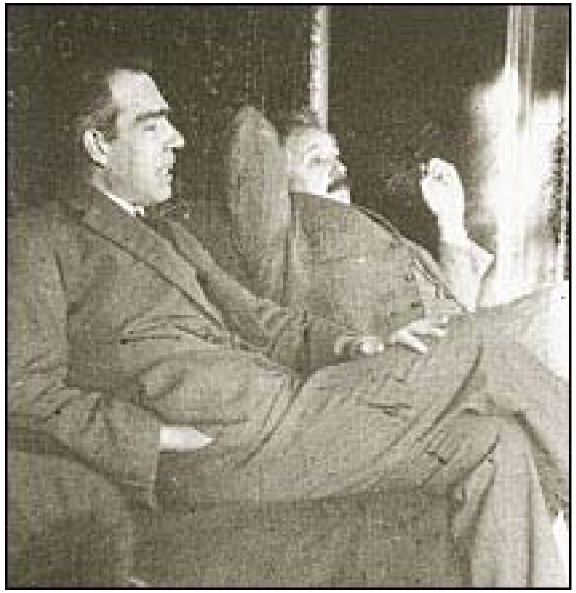
Can Quantum-Mechanical Description of Physical Reality be Considered Complete?

N. BOHR, *Institute for Theoretical Physics, University, Copenhagen*

(Received July 13, 1935)

It is shown that a certain "criterion of physical reality" formulated in a recent article with the above title by A. Einstein, B. Podolsky and N. Rosen contains an essential ambiguity when it is applied to quantum phenomena. In this connection a viewpoint termed "complementarity" is explained from which quantum-mechanical description of physical phenomena would seem to fulfill, within its scope, all rational demands of completeness.

Complementarity - instrumentation.



To measure

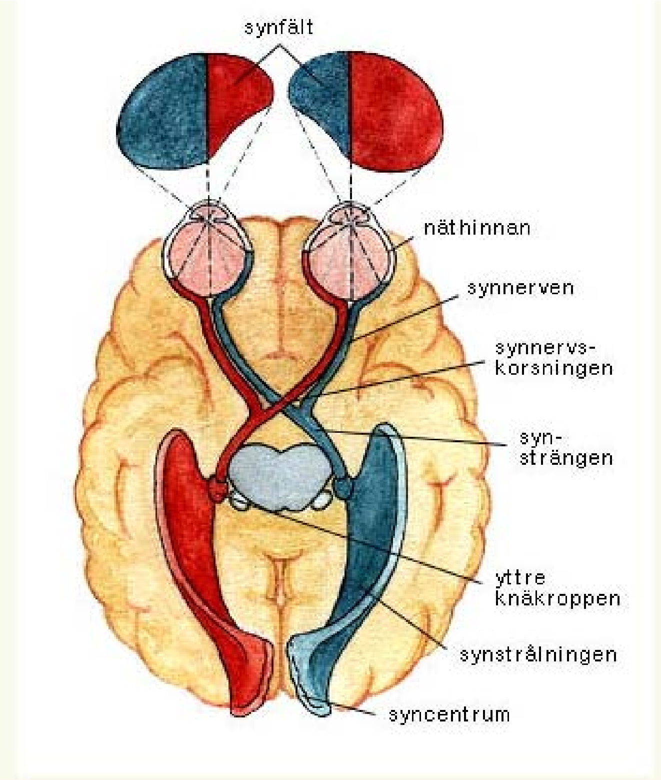
In-between science and philosophy

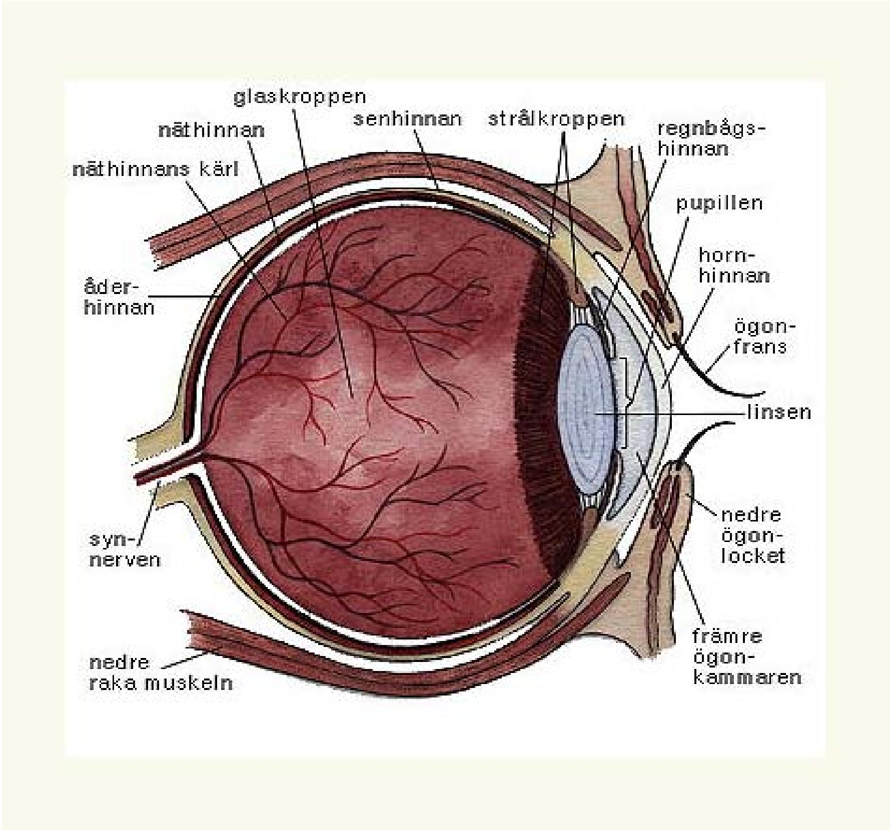
Our body has advanced sensors and analysis...

- Eyes (Photons)
- Ears (Changes in pressure and orientation)
- Smell (Chemicals, gasphase)
- Taste (Chemicals, fluids)
- Skin (Temperature, pressure (touch, vibratons))

Limitations and possibilities!

The photon detector

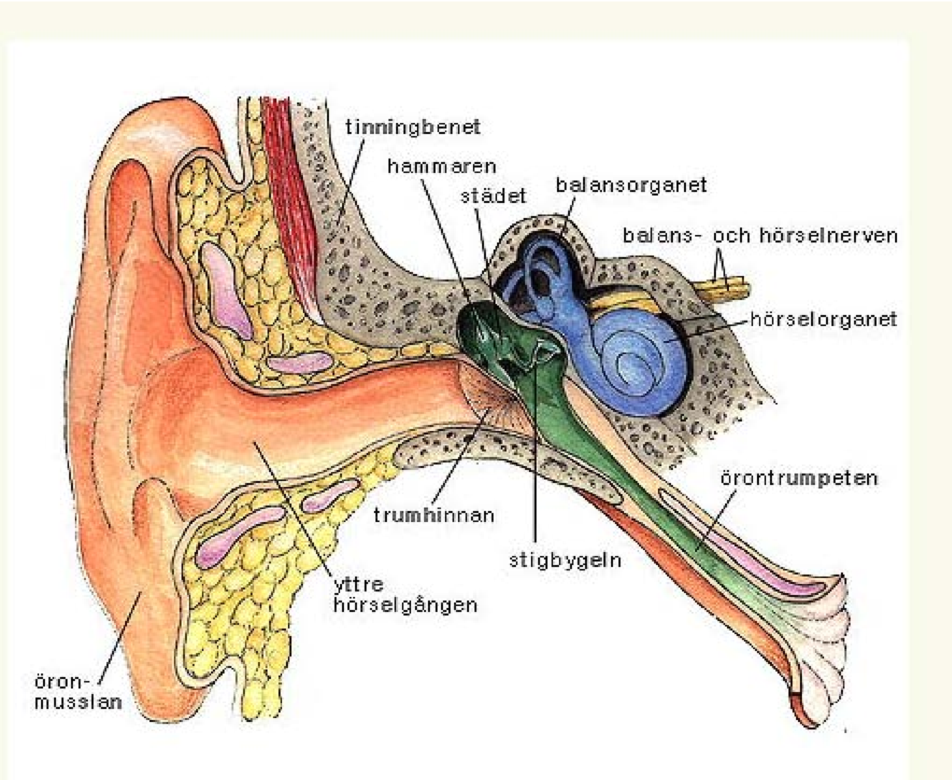


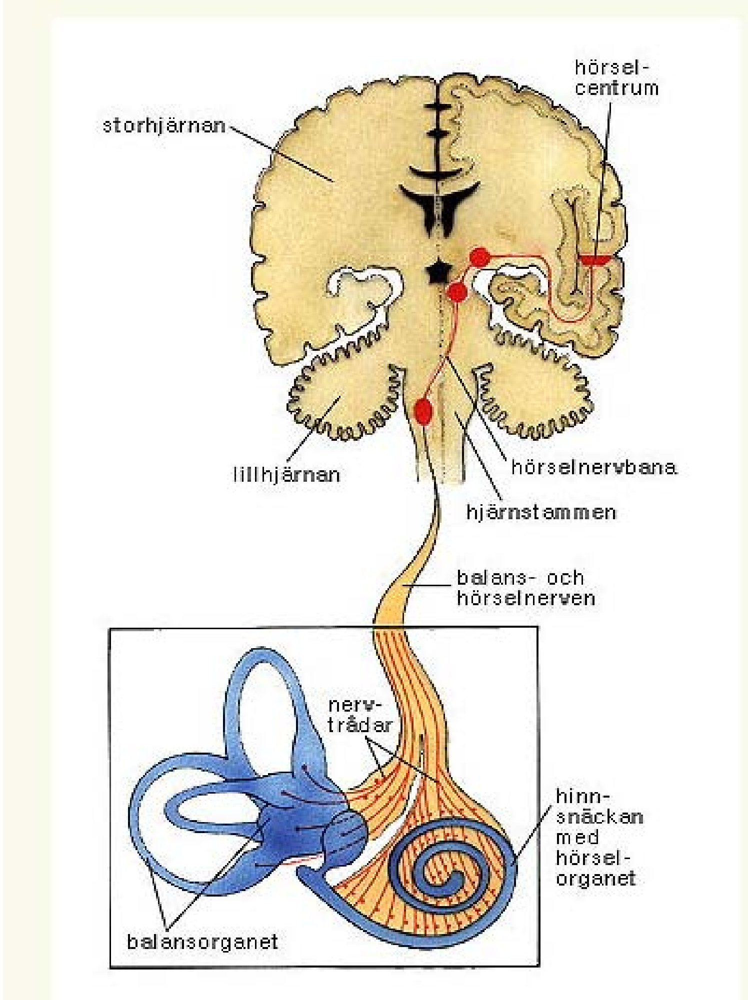


Range ≈ 0.4 -0.7 µm

NE

Differential pressure sensor

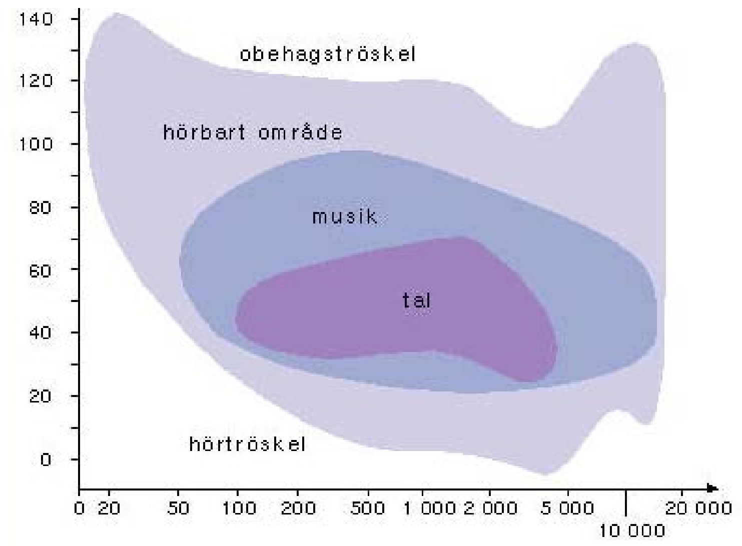




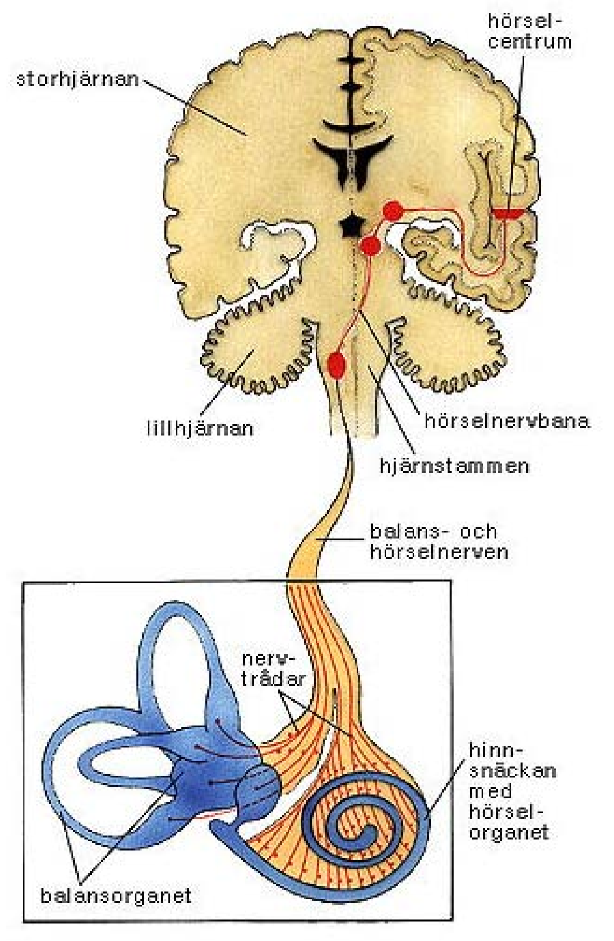
NE

Sensitivity and principles

Loudness (dB)



Frequency (Hz)



NE

Examples of what we want to measure

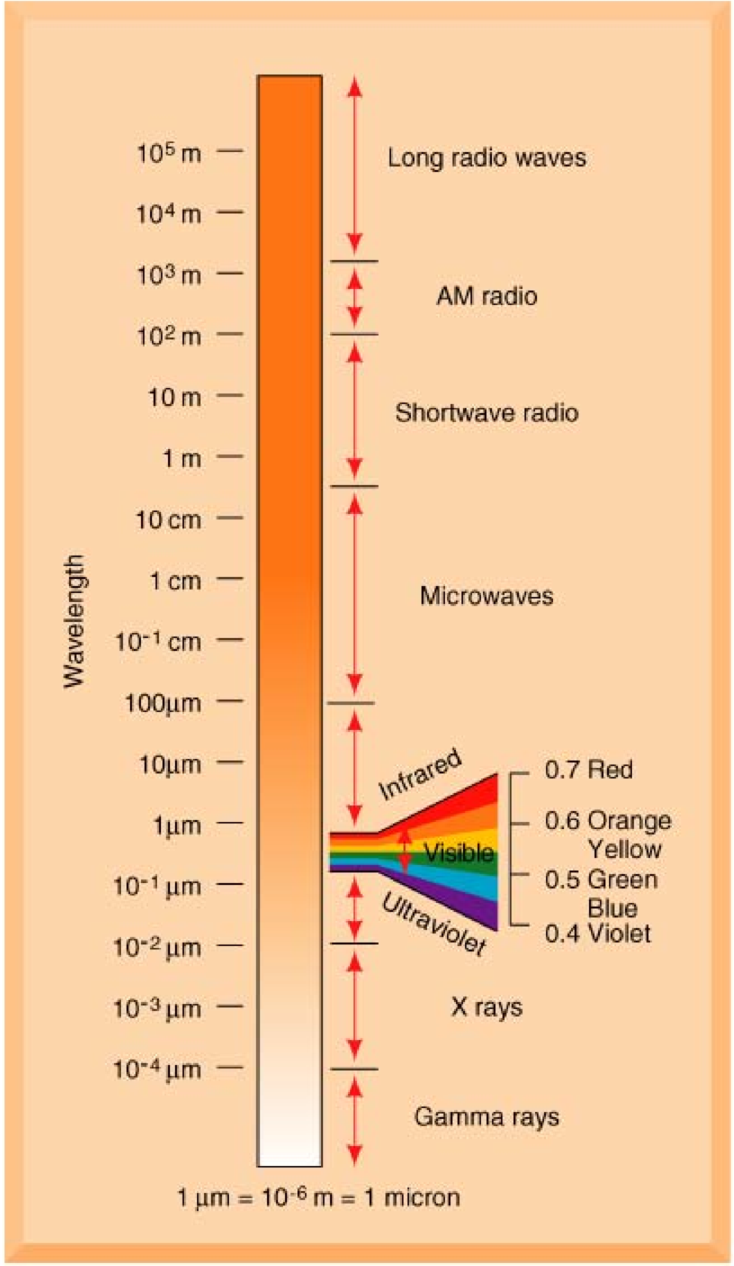


Figure 3.7 Types of electromagnetic radiation (EMR). Notice that the spectrum of wavelengths is over nine orders of magnitude, from radio waves to gamma rays (1µm = 10^{-6} m = 1 micron).

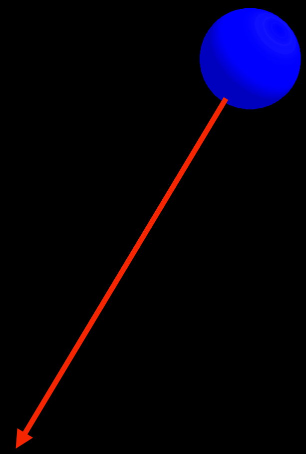
Radiation beyond the range 0.4-0.7 µm must be "transformed" prior to registration

- Electromagnetic radiation - Transformation in frequency
- Particles - Complete abstraction

Transformation

Mass, charge,

....



Particles

$E=mc^2$

1 eV - discuss

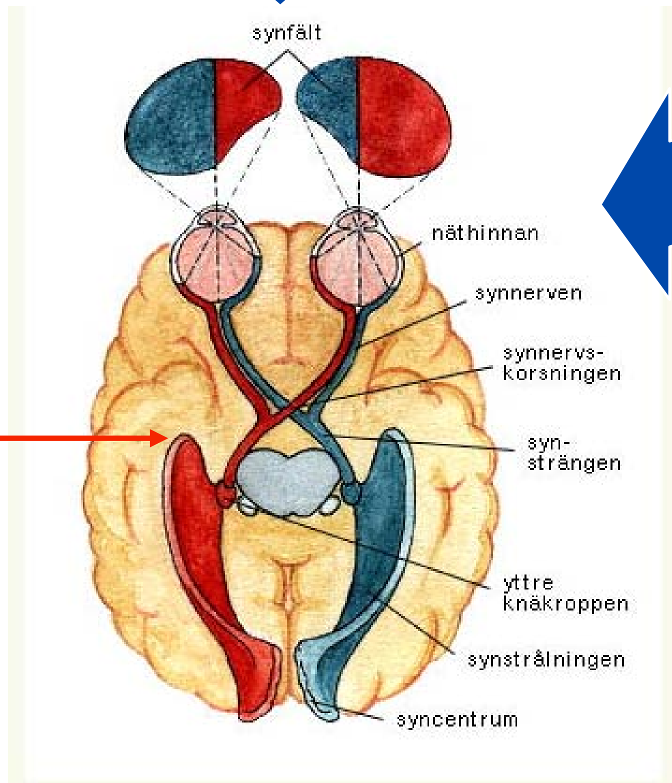
Speed, momentum

energy

Consequences

Event

Equipment -Filter

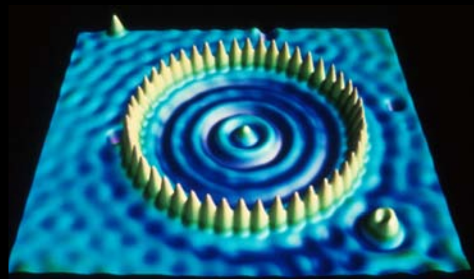


Theories

Describe the photo

Describe...

What is reality?



Thought experiment- "gedanken experiment"

Determine the position and energy of a particle in the darkest part of our universe!

Heisenberg (1927)

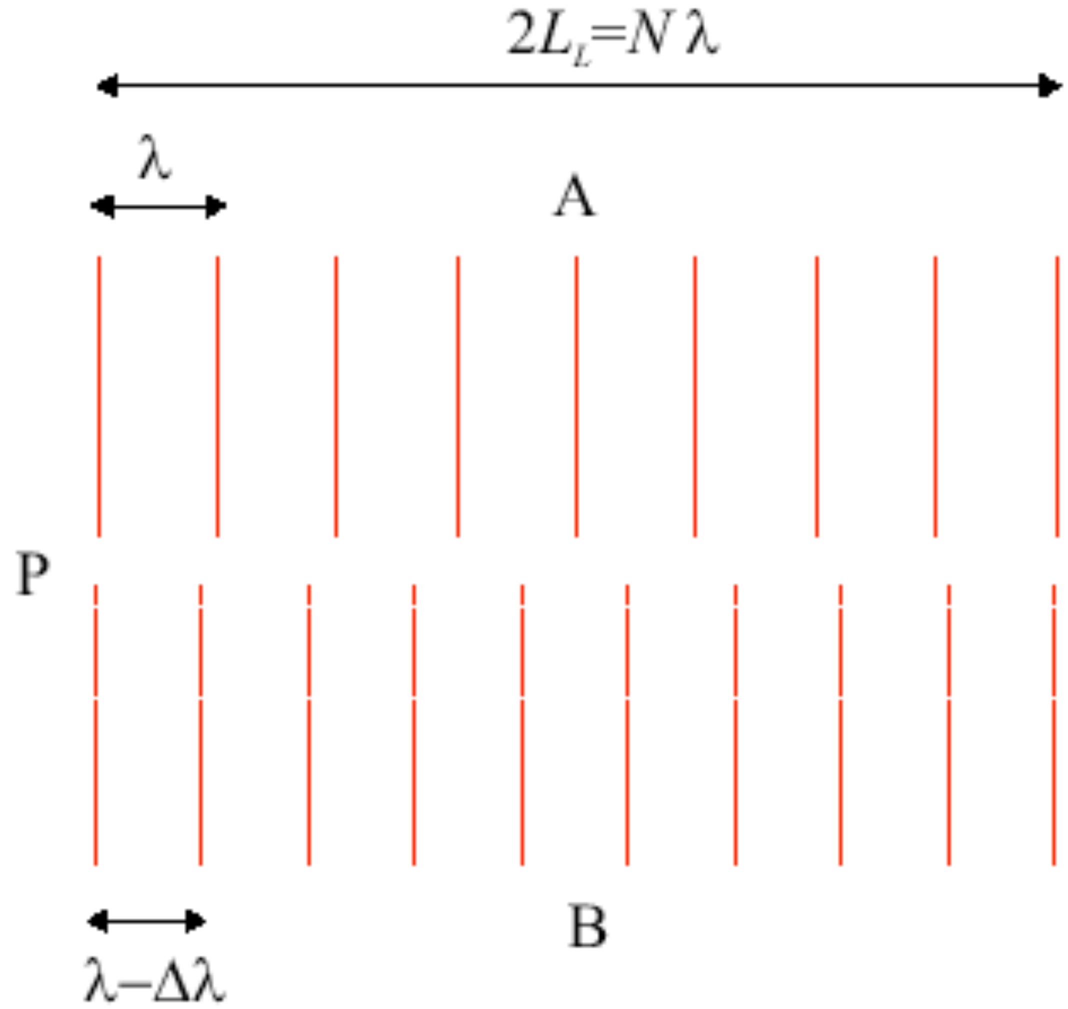
$$\Delta x \, \Delta p_x \geq \frac{1}{2}\hbar$$

$\approx 5 \; 10^{-35}$ Js $\approx 3 \; 10^{-16}$ eV s

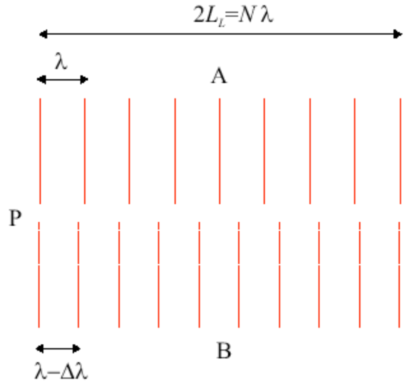
It is impossible to simultaneously determine the position and the momentum with an arbitrary accuracy.

Coherence (1)

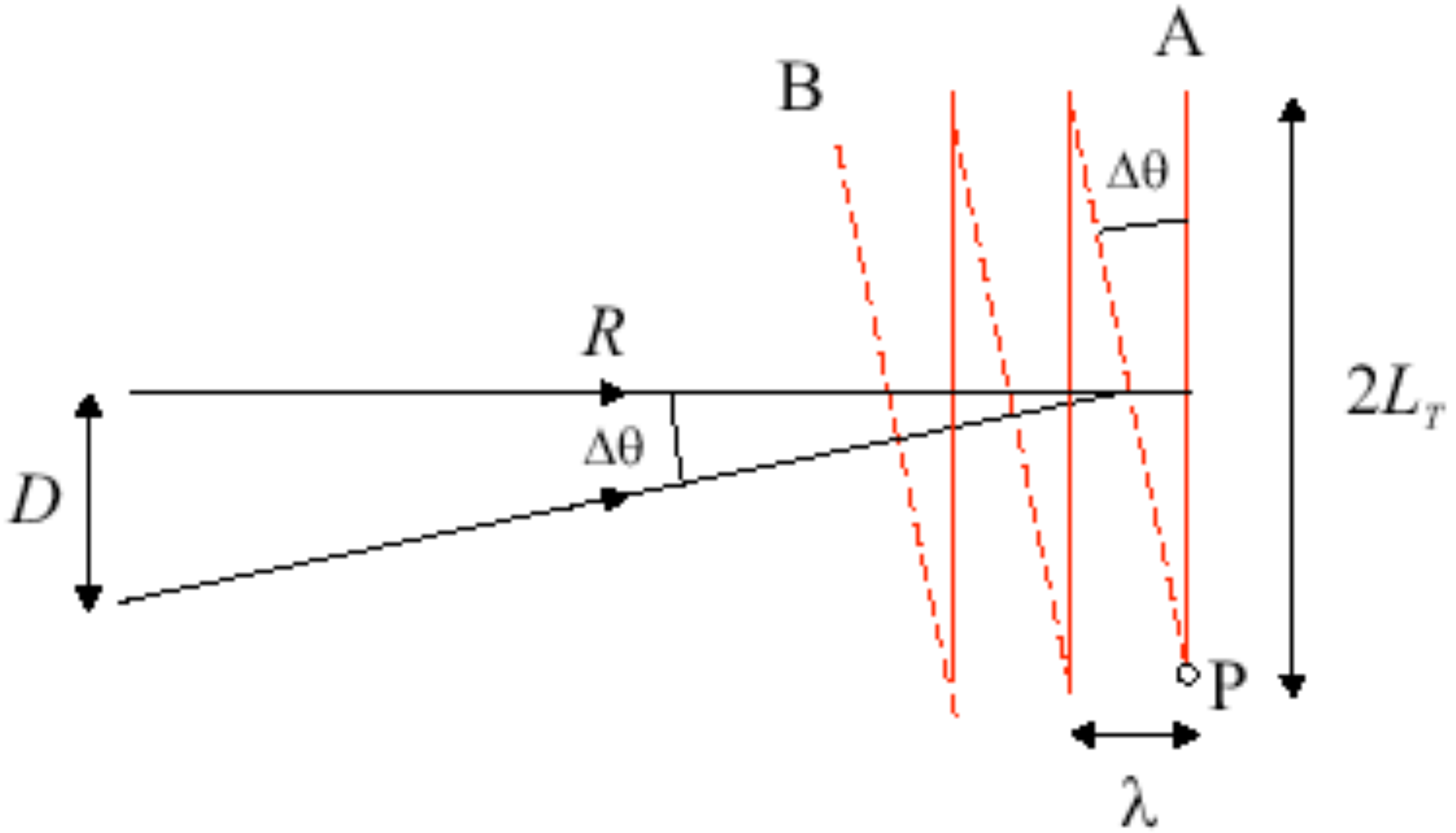
(a) Longitudinal coherence length, L_L



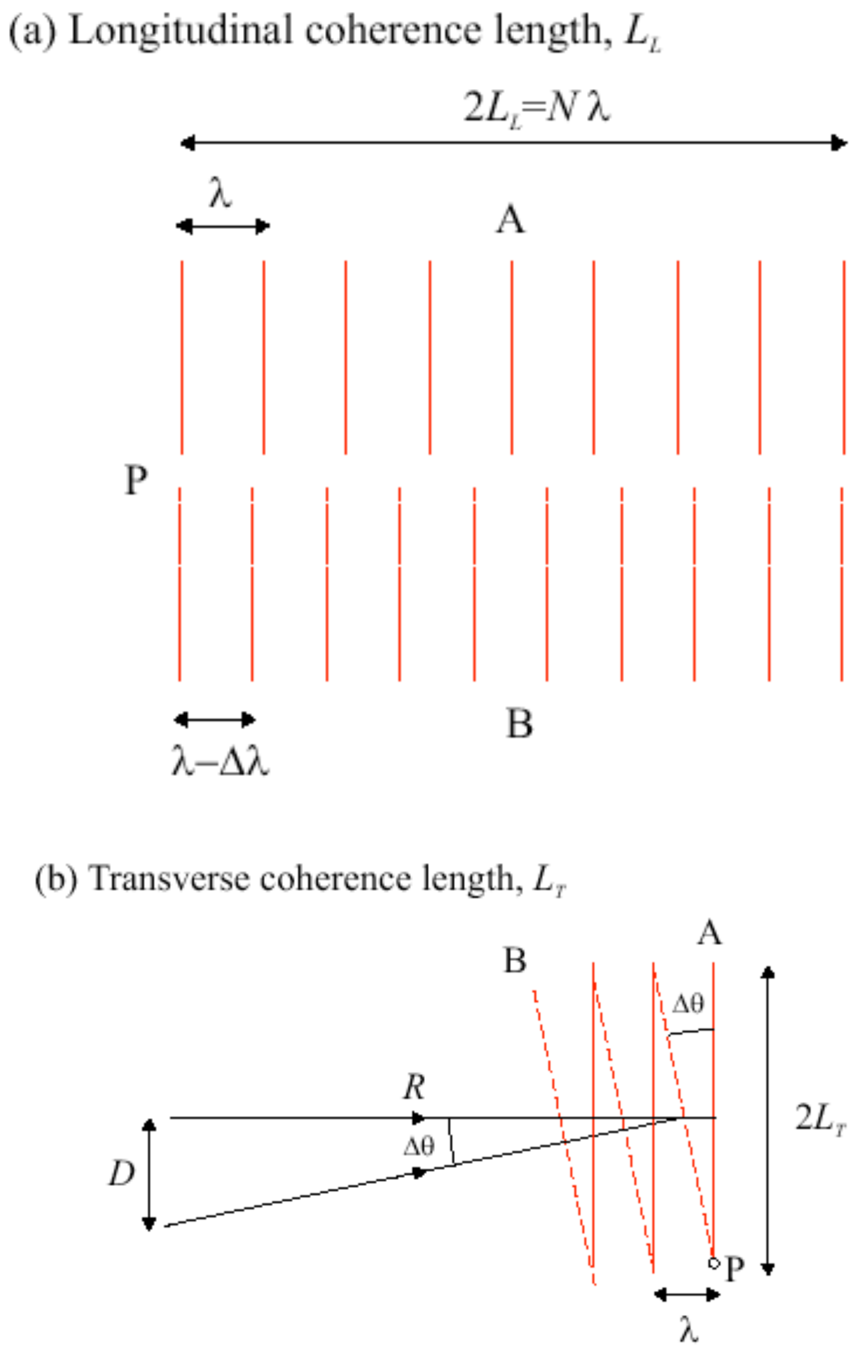
Coherence (2)



(b) Transverse coherence length, L_T



Coherence (3)



LASER

Parallel radiation with well defined energy & Phase coherency!

Reflectivity

Reflectivity - film on a substrate

P F Fewster

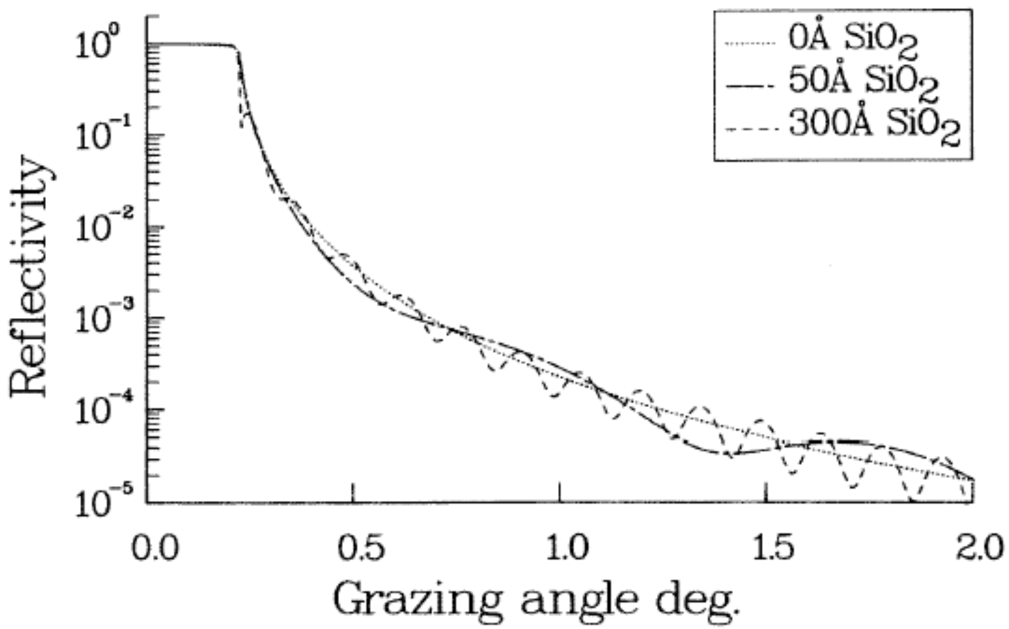
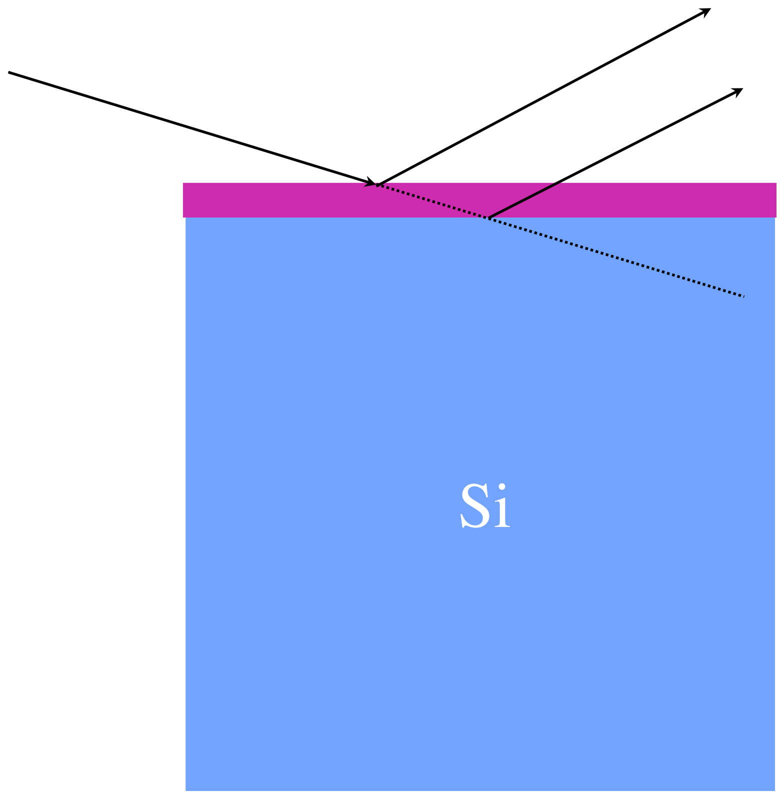
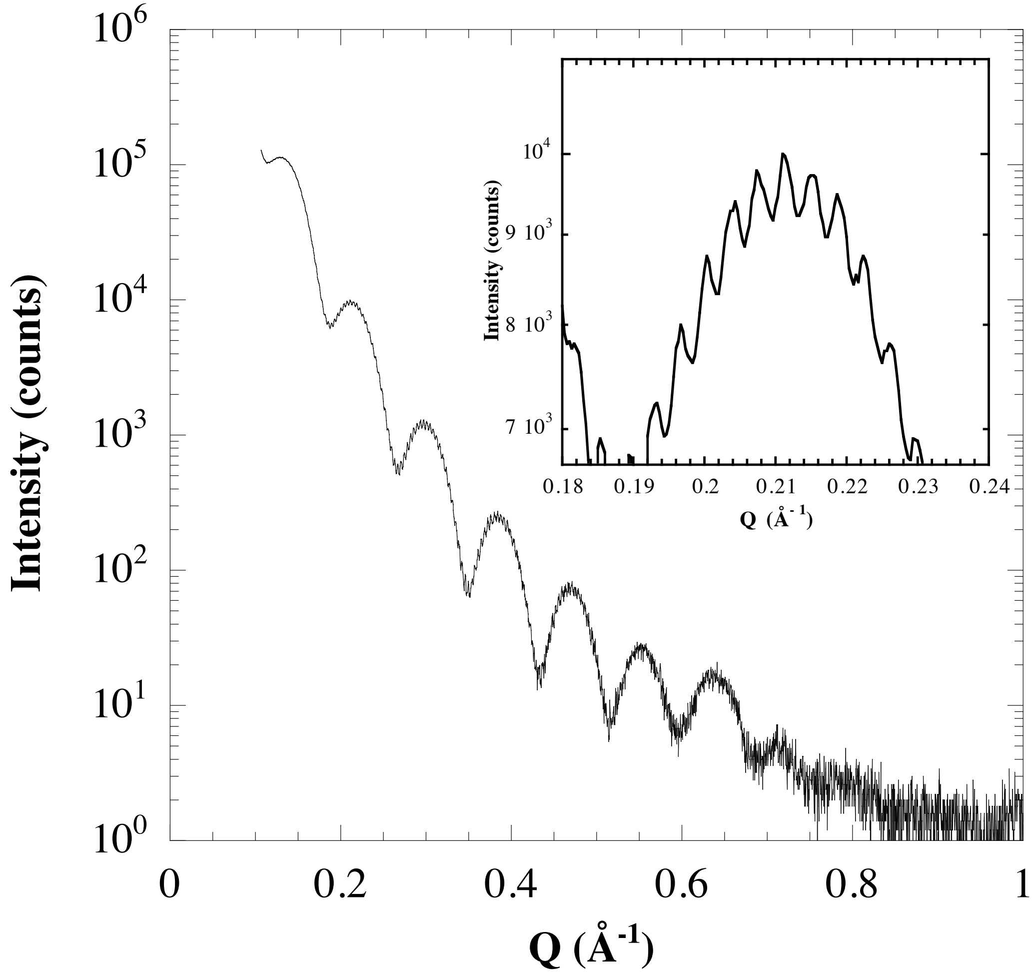
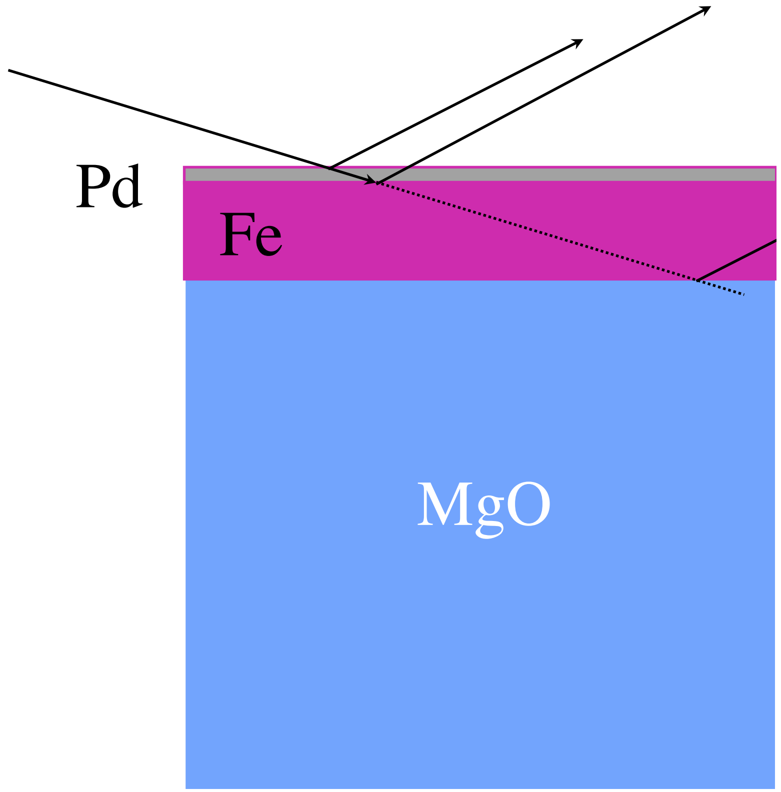


Figure 5. The change in fringe separation with thickness for a SiO_2 layer on Si in a reflectometry profile simulated for various layer thicknesses, CuKα radiation.



Reflectivity - Data





Neutrons (1)

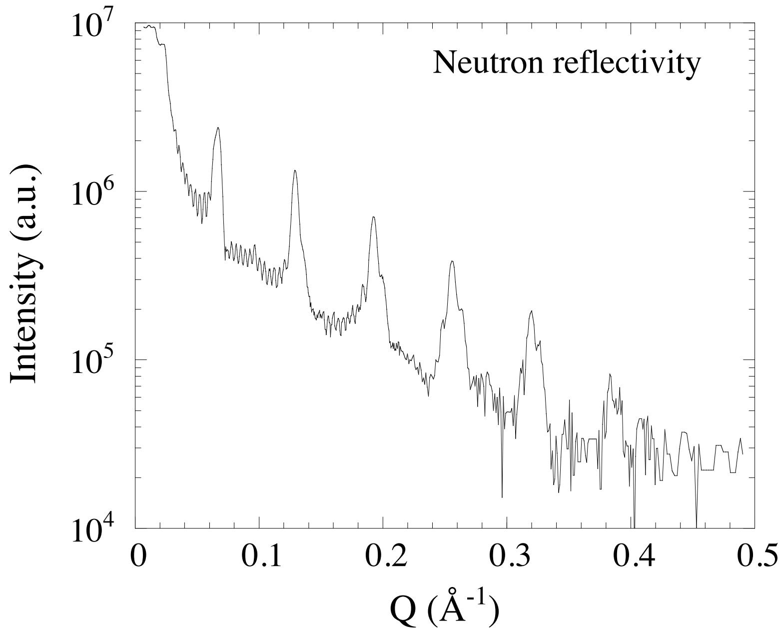
Neutrons are particles:

Mass ≈$1.67\ 10^{-27}$ kg (=1.00 u)

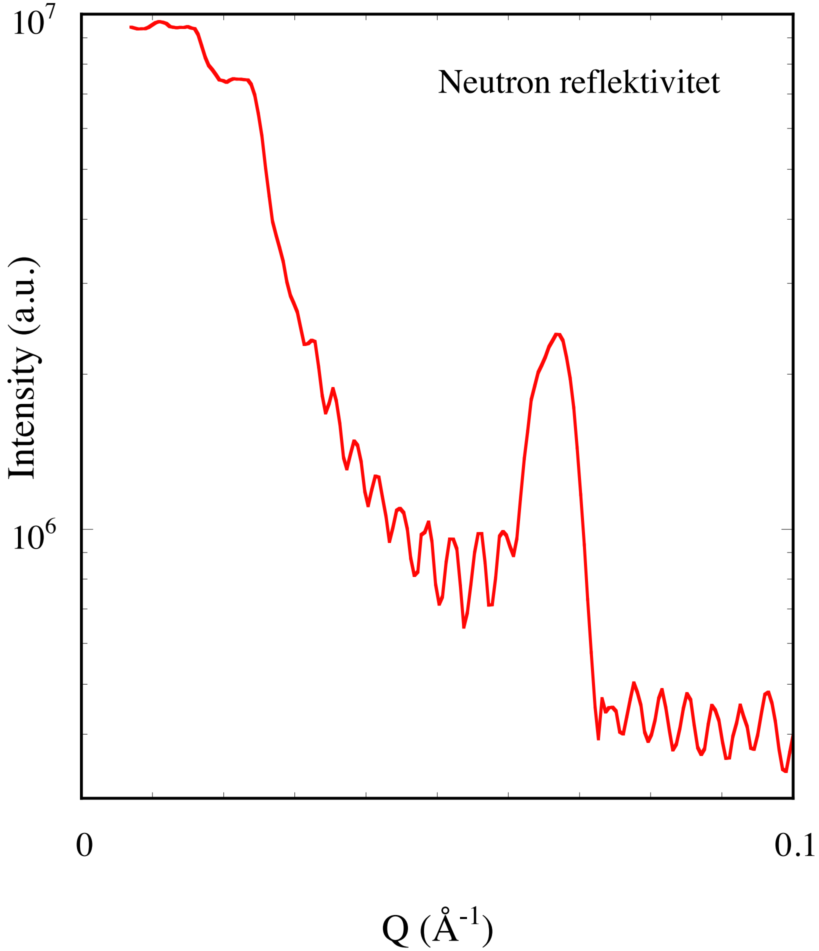
Extension ≈10^{-15} m

….

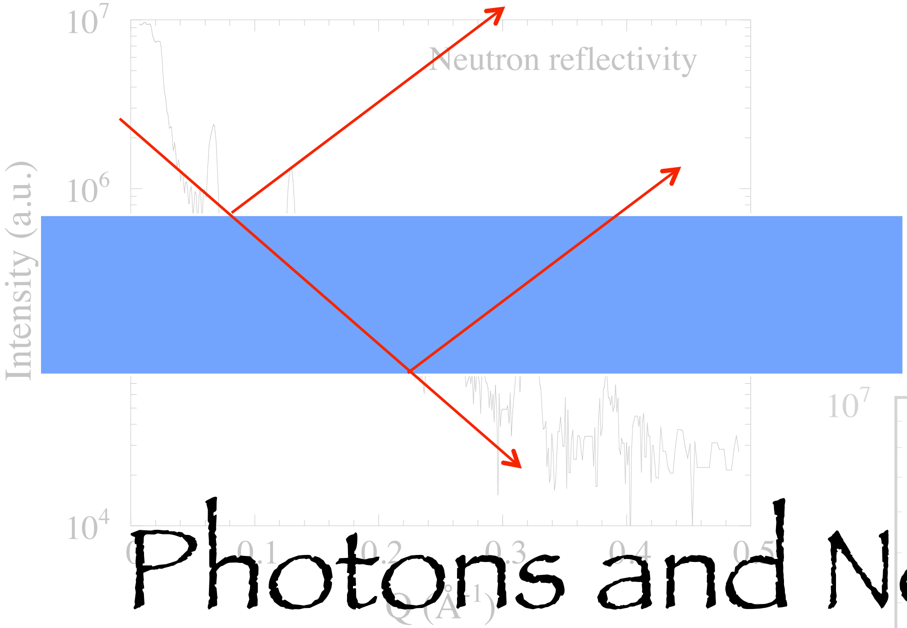
Neutrons (2)



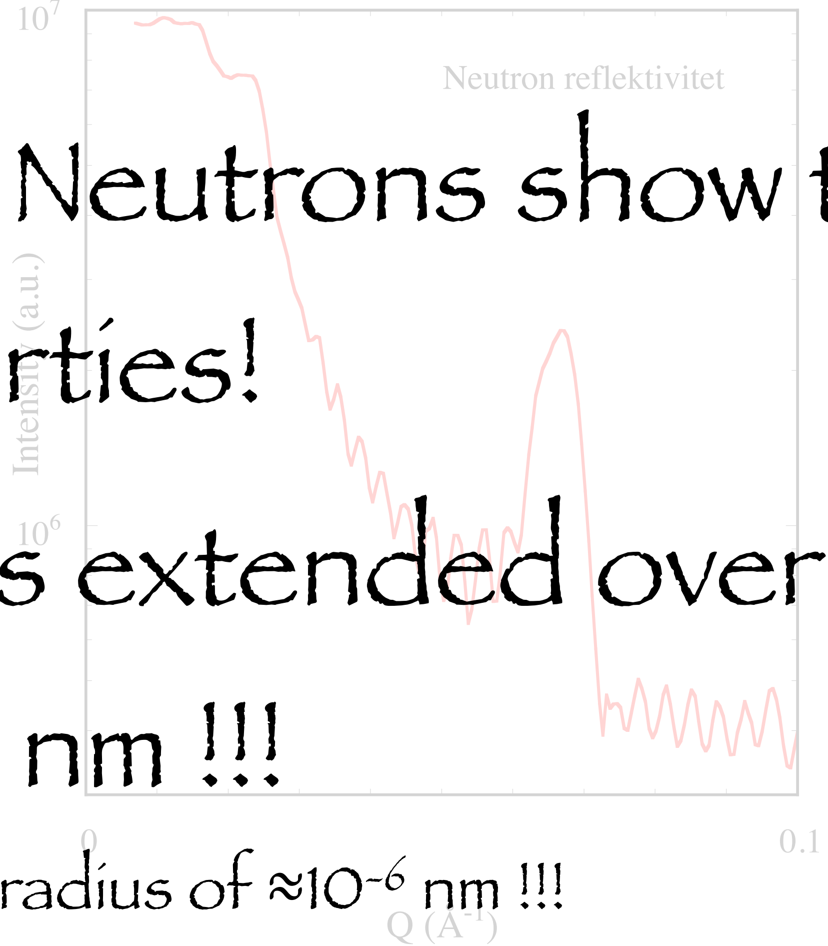
Neutron reflectivity
Intensity (a.u.)
10^7
10^6
10^5
10^4
0
0.1
0.2
0.3
0.4
0.5
Q (Å^-1)



Neutron reflektivitet
Intensity (a.u.)
10^7
10^6
0
0.1
Q (Å^-1)



Neutrons !

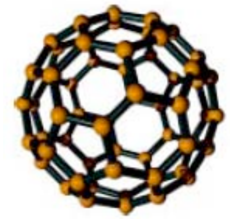


Photons and Neutrons show the SAME properties!

The neutron is extended over at least >>1000 nm !!!

Compare classical radius of ≈10^{-6} nm !!!

Quantum interference experiments with large molecules



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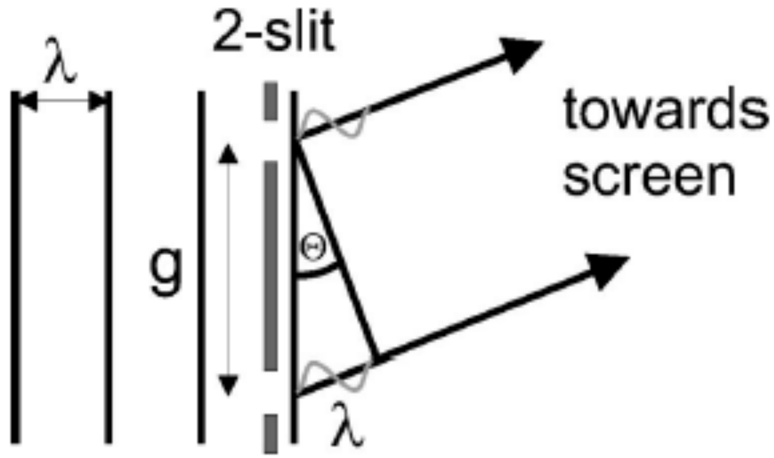
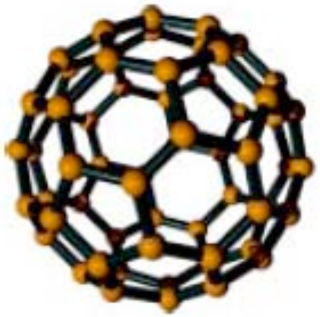
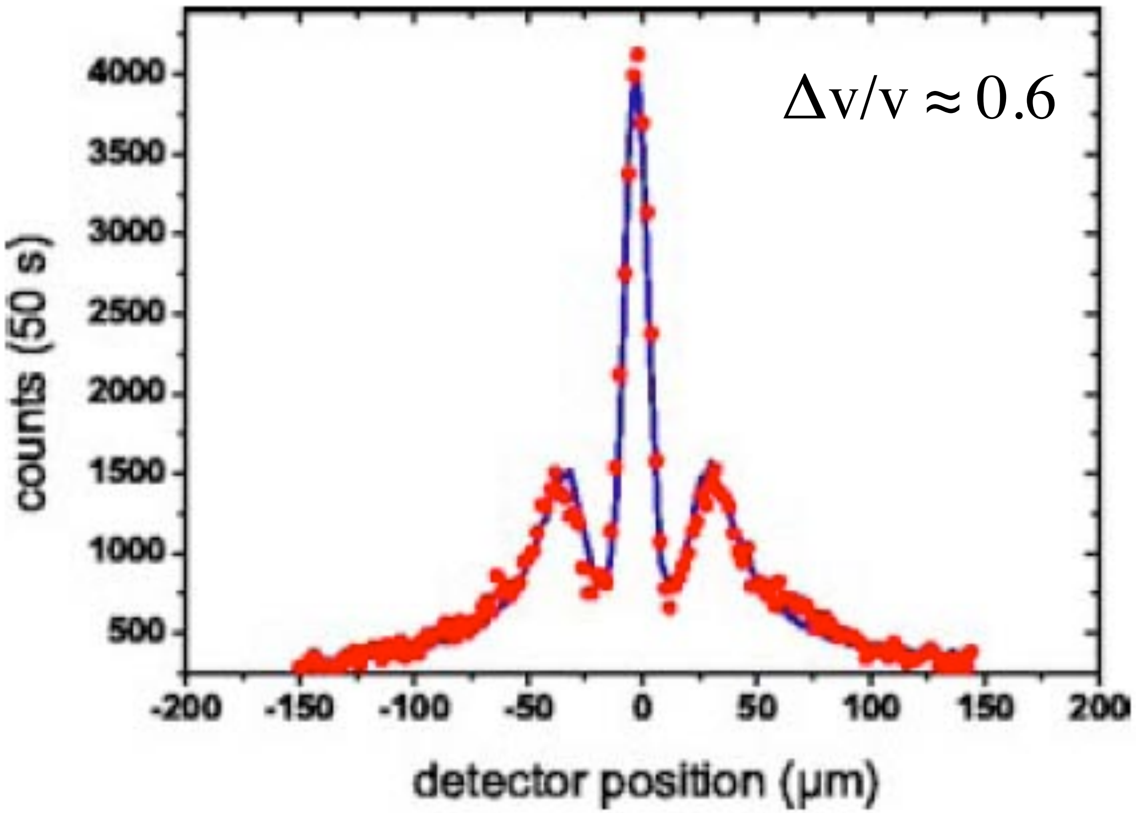
(Received 27 June 2002; accepted 30 October 2002)

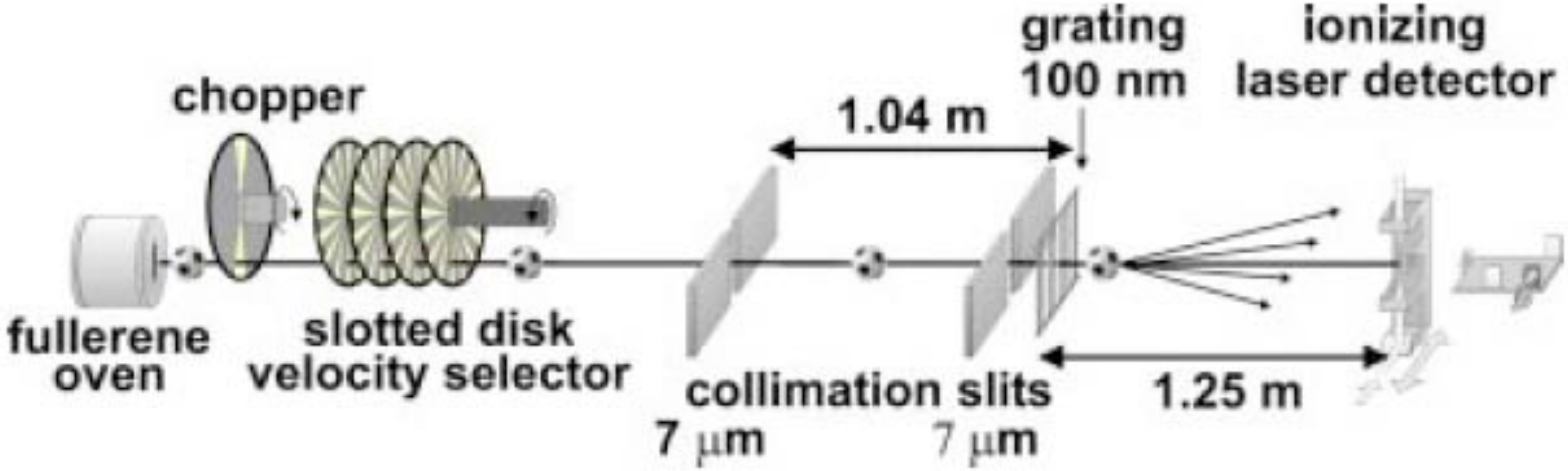
Think BIG!

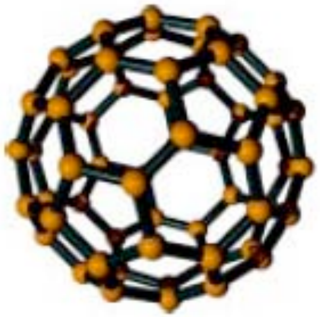
Wave–particle duality is frequently the first topic students encounter in elementary quantum physics. Although this phenomenon has been demonstrated with photons, electrons, neutrons, and atoms, the dual quantum character of the famous double-slit experiment can be best explained with the largest and most classical objects, which are currently the fullerene molecules. The soccer-ball-shaped carbon cages C_{60} are large, massive, and appealing objects for which it is clear that they must behave like particles under ordinary circumstances. We present the results of a multislit diffraction experiment with such objects to demonstrate their wave nature. The experiment serves as the basis for a discussion of several quantum concepts such as coherence, randomness, complementarity, and wave–particle duality. In particular, the effect of longitudinal (spectral) coherence can be demonstrated by a direct comparison of interferograms obtained with a thermal beam and a velocity selected beam in close analogy to the usual two-slit experiments using light.

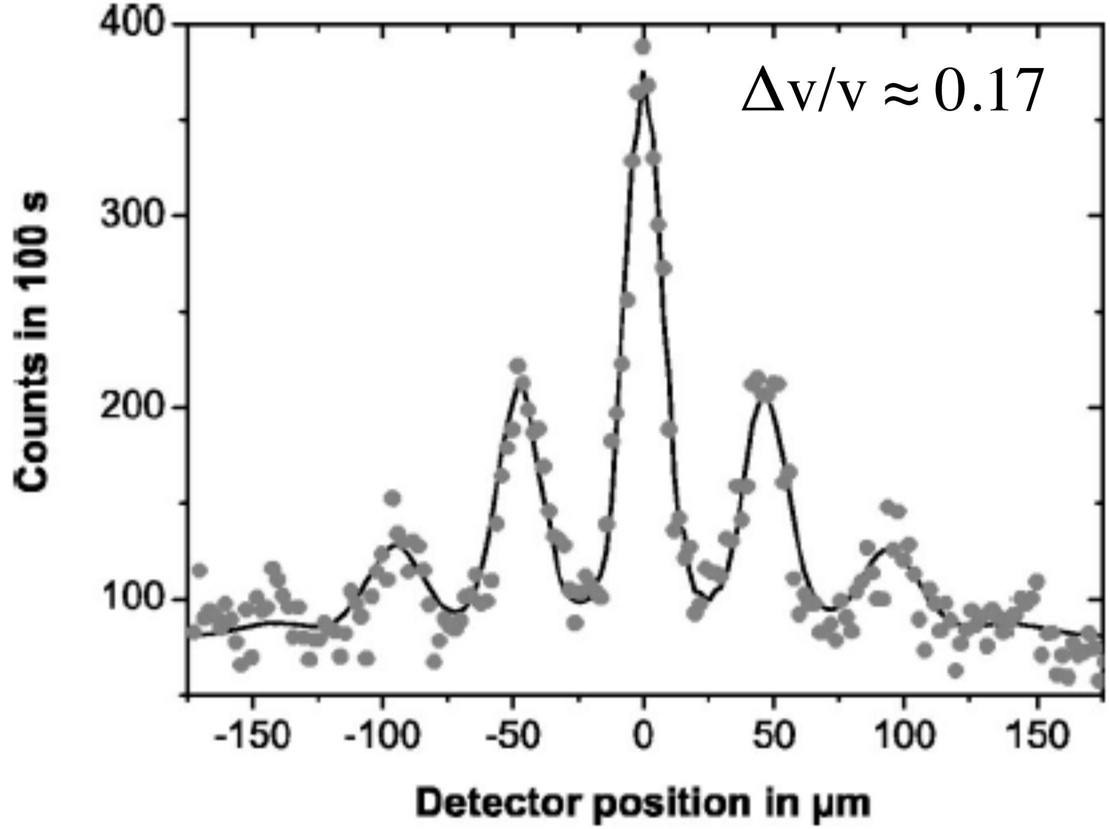


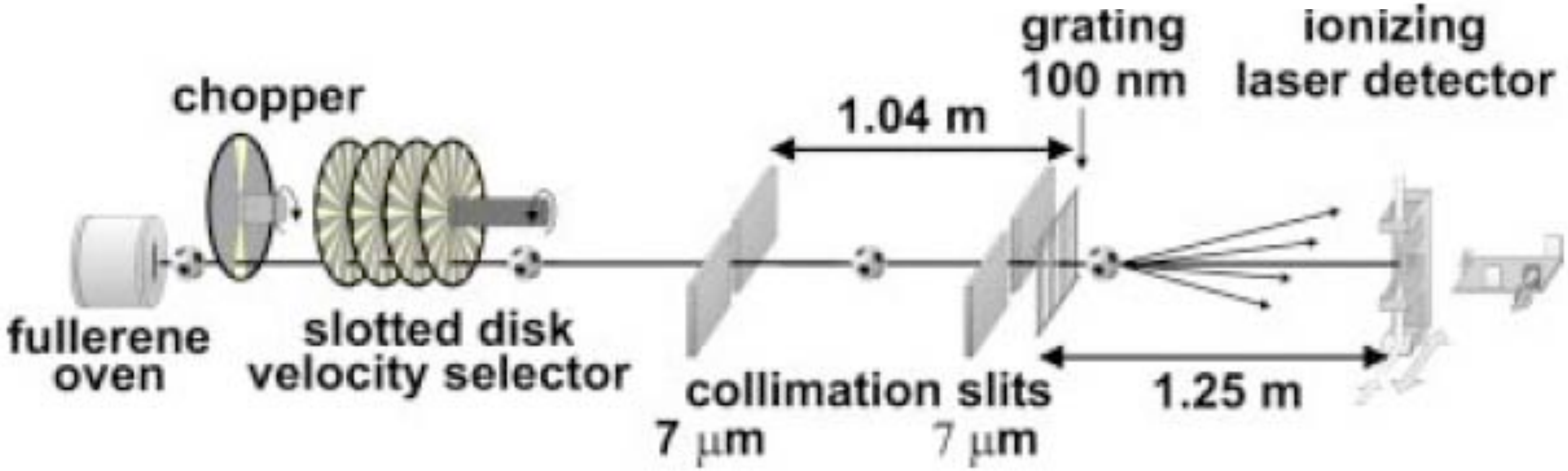


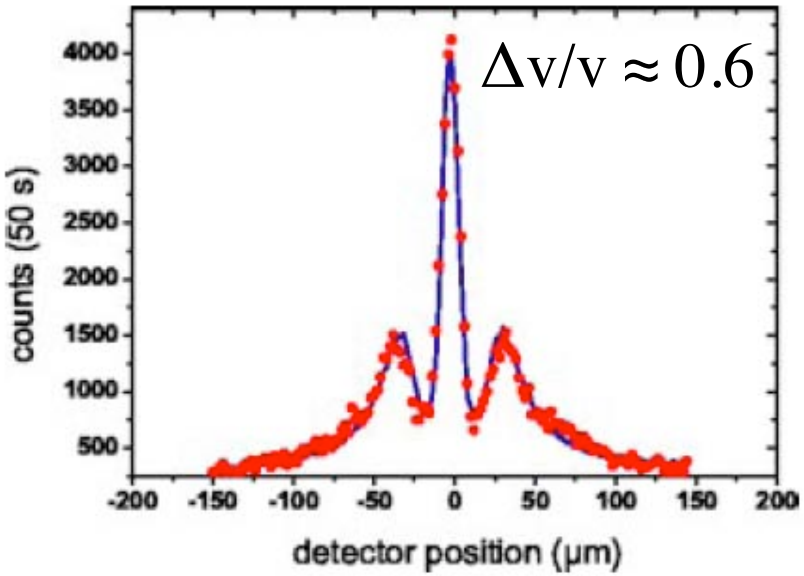

Δv/v ≈ 0.6
counts (50 s)
detector position (µm)
-200
-150
-100
-50
0
50
100
150
200
500
1000
1500
2000
2500
3000
3500
4000

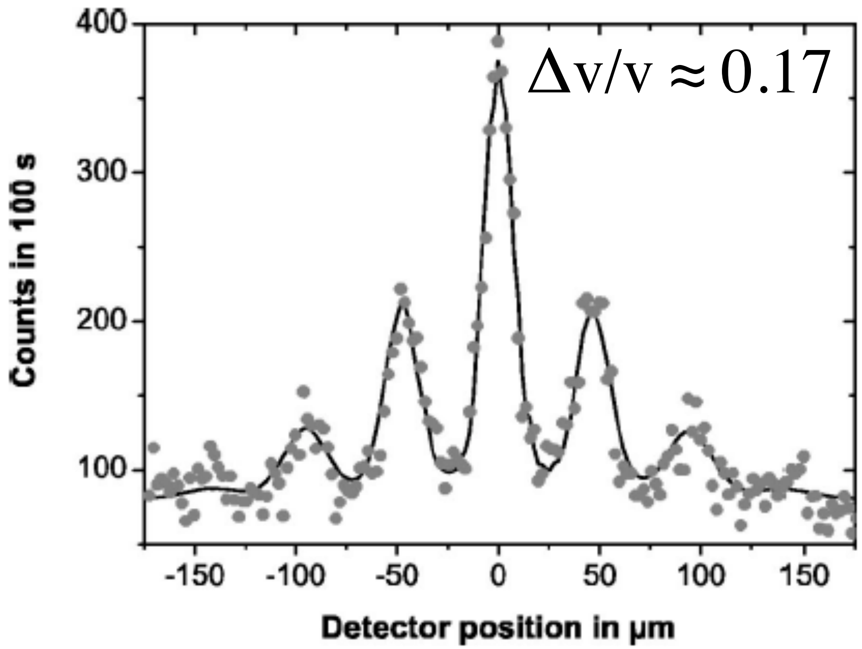

chopper
1.04 m
grating
100 nm
ionizing
laser detector
fullerene
oven
slotted disk
velocity selector
collimation slits
7 µm
7 µm
1.25 m



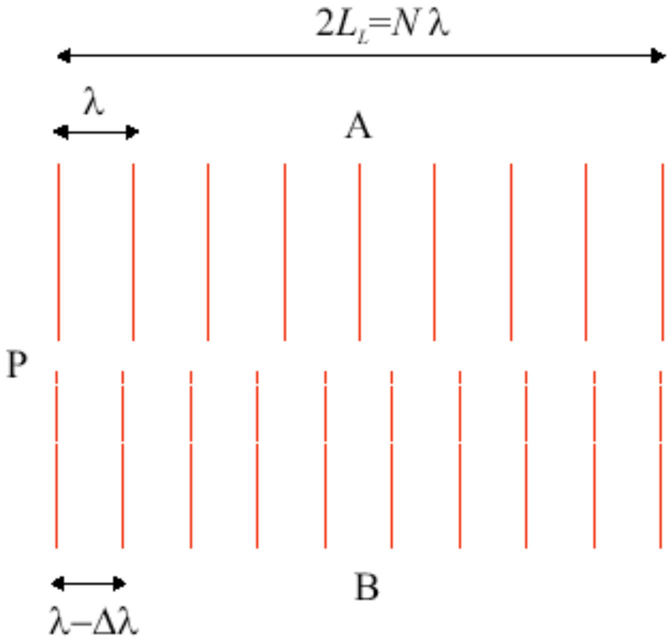

$\Delta v/v \approx 0.17$
Counts in 100 s
400
300
200
100
-150
-100
-50
0
50
100
150
Detector position in μm


chopper
1.04 m
grating
100 nm
ionizing
laser detector
fullerene
oven
slotted disk
velocity selector
collimation slits
7 μm
7 μm
1.25 m





(a) Longitudinal coherence length, L_L



$$\Delta x \, \Delta p_x \geq \frac{1}{2}\hbar$$

Heisenberg (2)

$$\Delta x \, \Delta p_x \geq \frac{1}{2}\hbar \qquad \Delta E \, \Delta t \geq \frac{1}{2}\hbar$$

Undeterminable ->
undeterminability

Compare - Los Alamos, -45.

Conclusions

- Undeterminability is determinable
- The principle of undeterminability is valid for photons, particles as well as big molecules.
- The border between undeterminability and uncertainty is the same as the border between the classical and the quantum world.

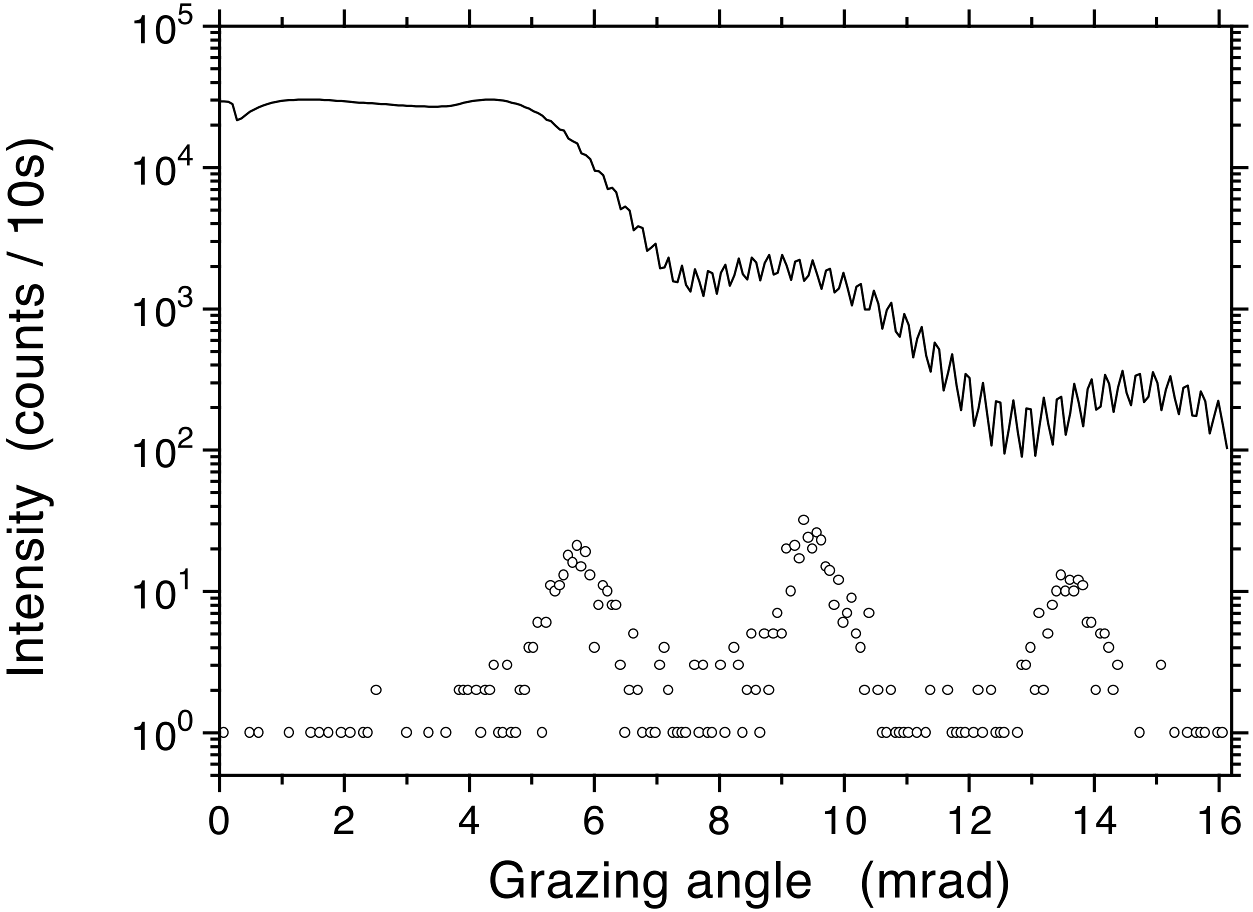
The End

Heisenberg (2)

$$\Delta x \, \Delta p_x \geq \frac{1}{2}\hbar$$

$$\Delta E \, \Delta t \geq \frac{1}{2}\hbar$$

• The big quiz / nuclear scattering



'igure 10. Angular dependence of nuclear (dots) and electronic (solid line) scattering of synhrotron radiation by a Pd(74)/[Fe(90)/^{57}Fe(10)]·15 superlattice on a MgO (100) substrate. The electronic reflectivity is divided by 1000. From [35].