CHAPTER 2: NANOMETROLOGY: STANDARDS AND NANOFACTURING

* Terminology

Nanometrology: The science of measurement at the nanoscale

- Measurand: the quantity subjected to measurement
- Accuracy: Ability to obtain the true value of a measurement. It does not reflect on the quality of the instrument.
- Preciscion: Ability to repeat measurements in the same way.
- Uncertainty: Associated to the result of a measurement, is a confidence level within which the measured value is expected to be
- Error: Disagreement btw measured value and true value. Error ≠ uncertainty. E.g. a measurement with a large uncertainty may have negligible error.
- Calibration: Process of determining the deviation of a measurement from that of an accepted standarized true value
- Traceability: Process to relate a result to a standard
- Accepted values or standards: Values accepted as standard (not true values)

METROLOGY AND MANUFACTURING (page 62)

Bound together. In order to mass-produce, one needs a clear set of guidelines for metrology and manufacturing from previous processes

Industrial revolution: Introduction of mass production (1800-1920)

- low-limit tolerance 1 mil (25µm)
- whole-scale mass production of all kind of products (clocks, guns, ...)
- Manufacturing tools designed to work with that low limit tolerance (machining, stamping, casting ...)
- Mechanical metrology - The Vernier caliper

Semiconductor revolution (1950)

- low-limit tolerance 1µm (or less ...), down to 100 nm (20nm now)
- Manufacturing went beyond mechanical. Optical and high energy beam systems required. (optical litho, ebeam, FIB)
- Advanced metrology (optical +)

Nanotechnology revolution (now ...)

- low-limit tolerance (1nm)
- Manufacturing for mass production of electronic, magnetic, photonic, chemical or mechanical systems at the nanoscale.
- Metrology at the nanoscale ...
- What happens with accuracy and uncertainty at this scale?

show slide 1 (evolution of machining) page 67

NANOMETROLOGY AND UNCERTAINTY

Metrology is divided in : 1) Theory
2) techniques
3) instrumentation
4) standards (legislation)

SI units : $[m] = kg$, $[t] = s$, $[i] = A$, $[T] = K$, $[r] = m$, $[\overset{\text{amount of}}{\text{substance}}] = mol$, $[\underset{\text{candela}}{I_v}] = cd$

These units are not enterely independent.

e.g. $1\,\Omega = 1\,m^2\,kg\,s^{-3}\,A^{-2}$

standards are important :

- For a long time the standard for the meter was in Paris

$1\,m = 10^{-7}$ distance from the equator to the North pole through the meridian passing by Paris !

standard : distance btw two marks in an iron bar kept in Paris

- in 1960, it was redefined as 1,650,763.73 wavelenghts of orange-red light in vacuum, produced by burning krypton (Kr-86)

- Currently, 1 meter is the distance light covers in vacuum in 1/299,792,458 seconds

↓ for which one needs the standard for a second

i.e., measured by a cesium-133 atomic clock

Reasons for standards being validated by natural constants:

- measurements don't depend on external conditions
- values do not drift with time
- measures can be reproduced anywhere

* The QHE + Josephson effects give two quantum standards from which the other basic seven standards can be obtained.

UNCERTAINTY

standard deviation μ_i is derived from the square root of the variance μ_i^2

At the nanoscale, one needs to take into account the Heissemberg Uncertainty Principle:

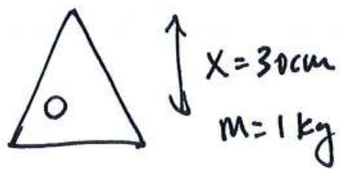
$$(\Delta E)(\Delta t) \gtrsim \hbar/2 \qquad (\Delta x)(\Delta p) \geq \hbar/2 \qquad \underline{\hbar \approx 10^{-34}\ J \cdot s}$$

In classical physics $\Delta x \to 0$ and $\Delta p \to 0$

When the system being measured is small, then both of these complementary quantities cannot be resolved with unlimited certainty.

Let's first do an example with $\hbar = 1 \Rightarrow \Delta x \Delta p \gtrsim 1$

Billiard ball inside a triangle



$\boxed{\Delta p \gtrsim 3\ m/s}$!!

with $\hbar = 10^{-34}$

$\boxed{\Delta p \gtrsim 10^{-34}\ m/s}$

QM. does not apply to macroscopic

let's look at the H atom

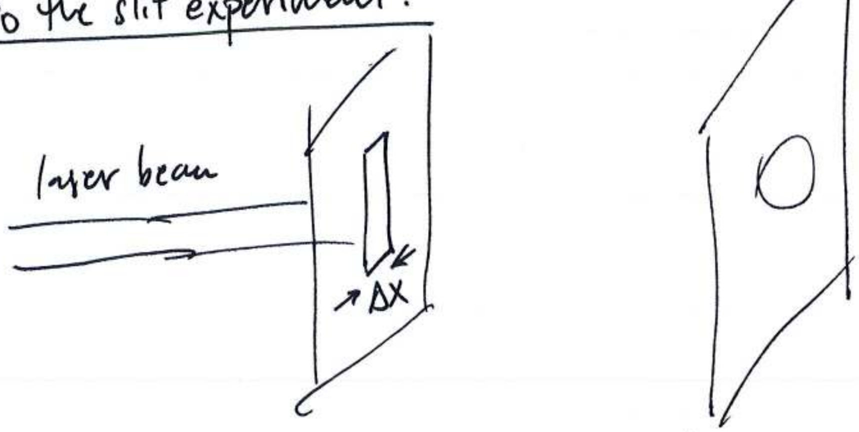
$\phi = 10^{-10}\,m = \Delta x$ $\qquad \underline{\Delta p} \geq \frac{\hbar}{\Delta x} = \frac{10^{-34}}{10^{-10}} = 10^{-24}\,kg\,m/s = \underline{m_e \Delta v}$

$m_e = 10^{-30}\,kg$

$$\boxed{\Delta v = \frac{10^{-24}\,kg\,m/s}{10^{-30}\,kg} = 10^{6}\,m/s\ !!}$$

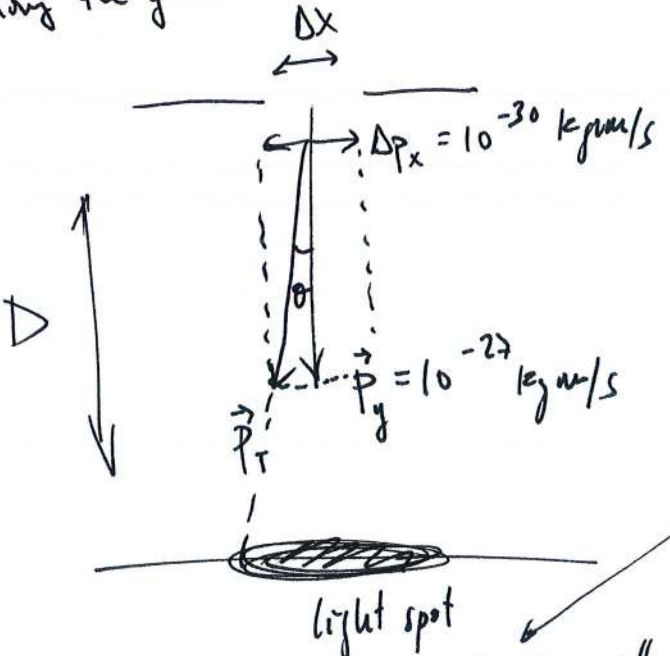
The electron is moving because is confined !!

Do the slit experiment:



$\Delta X \sim 10^{-4}\,m$ $\qquad \Delta p_x = \frac{10^{-34}}{10^{-4}} = 10^{-30}\,kg\,m/s$

$P_y = p_{photon} = 10^{-27}\,kg\,m/s$
momentum of incident photo along the y direction



$\sin\theta = \frac{\Delta p_x}{p_y} \sim \theta$

$\leftrightarrow$ $X_L = \theta D$ will increase as Δx goes down..

You may ask yourself, why do I care about the momentum if all I want is to measure de position?

- Let's measure an electron
- We need to use something to measure (a photon)
- $p = \frac{h}{\lambda}$ (of a photon)
- $\Delta p \sim \frac{h}{\Delta\lambda}$ or $\frac{h}{\Delta x}$ is the uncertainty in the electron's momentum after the collision, therefore $\boxed{\Delta x \, \Delta p \geqslant h}$

Numerical example:

A free electron has kinetic energy $K = 25\,\text{eV}$. If the velocity is known with 0.5% of accuracy, what is ~~the~~ Δx of the position of the electron?

$$K = \frac{1}{2} m_e v^2 = 25\,\text{eV} = 25 \underbrace{\left(1.6\times10^{-19}\,\text{C}\right)}_{e} \underbrace{\left(\frac{\text{J}}{\text{C}}\right)}_{\text{V}} = 4\times10^{-18}\,\text{J}$$

$$v = \sqrt{\frac{2K}{m_e}} = \sqrt{2\left(\frac{4\times10^{-18}\,\text{J}}{9.1\times10^{-31}\,\text{kg}}\right)} = 3.0\times10^{6}\,\text{m/s}$$

$$\Delta p = 0.5\%\, p = 0.005 \times m_e v = 0.005 \times 9.1\times10^{-31}\,\text{kg} \cdot 3\times10^{6}\,\text{m/s} = 1.4\times10^{-26}\,\text{kg m/s}$$

$$\boxed{\Delta x \approx \frac{h}{\Delta p} = \frac{6.6\times10^{-34}\,\text{J s}}{1.4\times10^{-26}\,\text{kg m/s}} = 47\,\text{nm}}$$ substantial for atomic scales

Ask students to check on an example for a bullet (macroscopic). The minimum uncertainty there is irrelevant for the measurement.

Do not talk about entanglement - just mention it
Jump over quantum metrology as well (section 2.2 of the book)

NANOMETROLOGY TOOLS (SECTION 2.3 IN BOOK)

Assign homework to students. Each student should explain one topic in class. 5 minutes time limit (3 slides).

* List of topics from Nanometrology tools:

- Electron-beam microscopy
- Scanning probe microscopy - AFM
- Scanning probe microscopy - STM
- Spectroscopy - X-ray sources (syncrotron)
- Spectroscopy - nano/surface Raman
- spectroscopy - single-molecule detection

* List of topics from nanofactoring tools:

- Optical lithography
- Electron-beam lithography
- Nano manipulators
- Focused ion beam
- Optical twizers