Quantum phenomena

By
Dr. T. U. Urunkar M.Sc., Ph.D.

Vivekanand College, Kolhapur
(Empowered Autonomous)

Date : 07/08/2023

Learning outcomes

- explain atomic line spectra in terms of electron energy levels and a photon model of electromagnetic radiation
- describe and explain the photoelectric effect, $hf = \phi + E_{k\,\max}$
- provide evidence of the wave nature of electrons and describe how their wavelength depends on speed $\lambda = \dfrac{h}{mv}$
- describe radioactive decay, fission and fusion in terms of nuclear binding energy and mass defect $E = \Delta mc^2$
- explain how quantum theory differs from classical physics
- solve related quantitative problems
- connect and use an electron diffraction tube

Teaching challenges

- Whereas classical physics rewards students who can picture what is happening, quantum theory defies visualisation.
- Abstract and counter-intuitive ideas need to be linked to visible phenomena and devices, including some already familiar to students.
- Most A-level specifications trivialise the teaching of quantum phenomena and fail to distinguish it properly from classical physics.

Scientific explanation

- correlates separate observations
- suggests new relations and directions
- gives testable hypotheses (empirical ‘acid test’)

Unifications in physics

<table>
<tr>
<td>Mechanical theory
(Newton, 1687)
Entities: particles, inertia, force that lies along a line between interacting particles.</td>
<td>Electromagnetic theory
(Maxwell, 1864)
Entities: electric & magnetic fields, force that is perpendicular to both field & motion.</td>
</tr>
<tr>
<td>· celestial motions
· terrestrial motions, in 3-D
· heat (kinetic theory)</td>
<td>· magnetism
· electricity
· optics</td>
</tr>
<tr>
<td colspan="2">Relativity theory (Einstein, 1905 & 1916) unites <u>all</u> phenomena above</td>
</tr>
<tr>
<td colspan="2">Quantum theory
(Planck 1900; Einstein 1905,16,17; Bohr & Heisenberg 1925; Schrodinger 1926; Dirac 1927; Bethe, Tomonaga, Schwinger, Feynman & Dyson 1940s …)
· atoms and nuclei
Dissolves the classical distinction between point particles & non-local fields/waves. Quantum objects manage both at once.</td>
</tr>
</table>

The end of the mechanical age

1. Things move in a continuous manner. All motion, both in the large and small, exhibits continuity.
2. Things move for reasons. All motion has a history, is determinable and predictable.
3. The universe and all its constituents can be understood as complex machinery, each component moving simply.
4. A careful observer can observe physical phenomena without disturbing them.

Inside atoms, all of these statements proved false.

What went wrong?

Classical physics could not explain

- line spectra
- electron configuration in atoms
- black body radiation
- photoelectric effect
- specific thermal capacity of a crystalline solid
- Compton scattering of X-rays

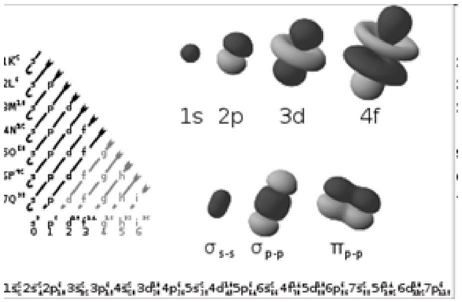
‘Quantum theory’

Quantum mechanics (electrons in atoms i.e. Chemistry, superconductors, lasers, semiconductor electronics)

Quantum field theory

… interactions mediated by messenger particles

- quantum electrodynamics (interactions of light & matter, interactions of charged particles, annihilation & pair production)
- electroweak unification (weak force + electromagnetism)
- quantum chromodynamics (quarks & gluons)



Explains everything except gravity.

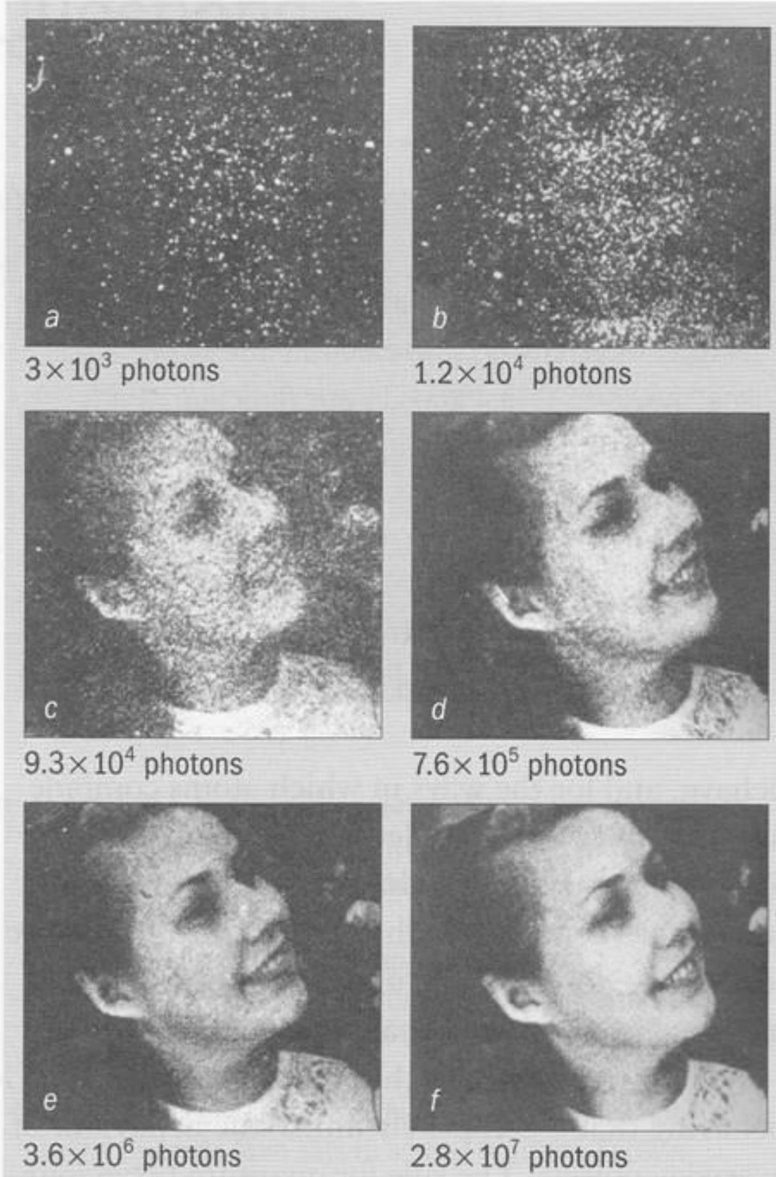
Quantum theory in essence

- entities: system with discrete states, physically-observable quantities (events)
- only the probability of events is predictable
- whatever happens in between emission and absorption, light is always emitted and absorbed in discrete amounts of energy.

Einstein: ‘God does not play dice.’

Feynman: ‘things on a small scale behave *nothing like* things on a large scale.’ ‘I hope you can accept Nature as She is – absurd.’

Bohr: ‘Anyone who is not shocked by quantum theory has not fully understood it.’


a
3×10^3 photons
b
1.2×10^4 photons
c
9.3×10^4 photons
d
7.6×10^5 photons
e
3.6×10^6 photons
f
2.8×10^7 photons

How photons travel

Photons seem to obey the command ‘explore all paths’. All the possibilities can be added up in a special way and used to predict what happens.

Particle physics

The same approach is used to work out how quantum particles

- change into one another - neutron (udd) decays to proton (uud)
- interact with one another - electrons repel by exchanging a photon

Scientists agree to differ

Agreed formalism, different interpretations

Does the quantum world really exist, or is there only abstract quantum physical description?

Responses include:

- Copenhagen interpretation (there is no objective reality; a quantum system has no properties until they are measured)
- ‘many worlds’ (all things happen, in a branching universe)
- non-local, hidden variables (an attempt to restore realism)

Line spectra

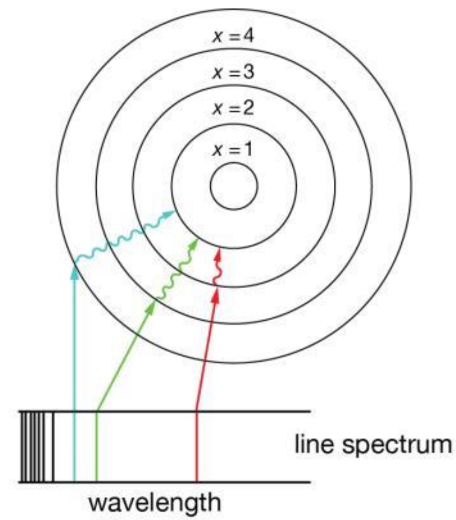
There is a 'ladder' of energy levels in the atom.

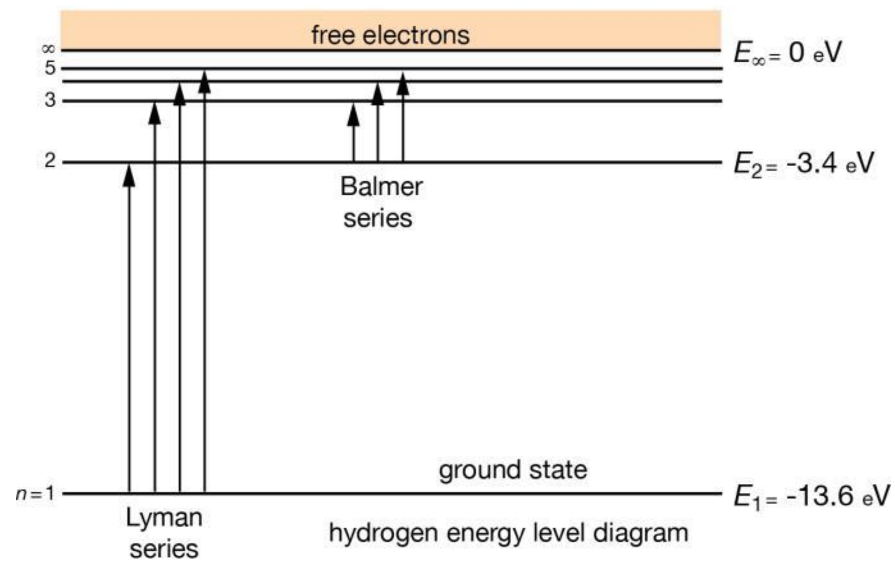
Changes in electron arrangement correspond to the emission or absorption of a photon.

$$E_2 - E_1 = hf = \frac{hc}{\lambda}$$

where *h* is the Planck constant, 6.6×10^{-34} Js

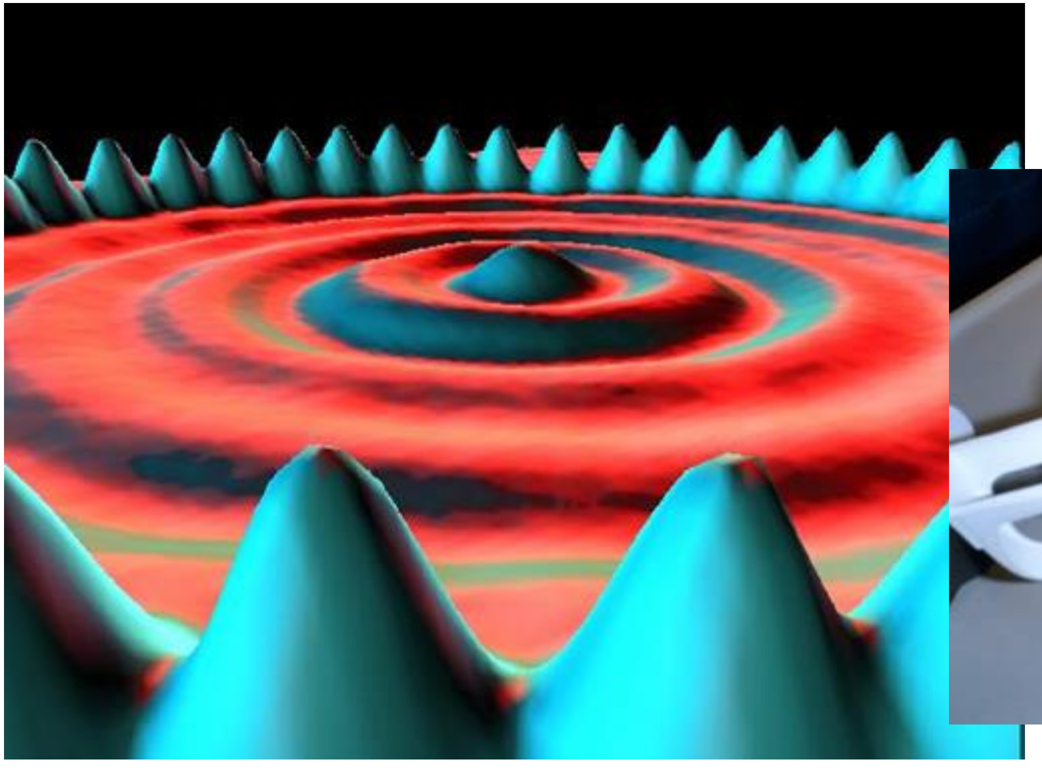
energy unit: electronvolt (eV)





Probability waves for electrons

STM image. Electron density waves in a corral of 48 iron atoms on a copper surface.



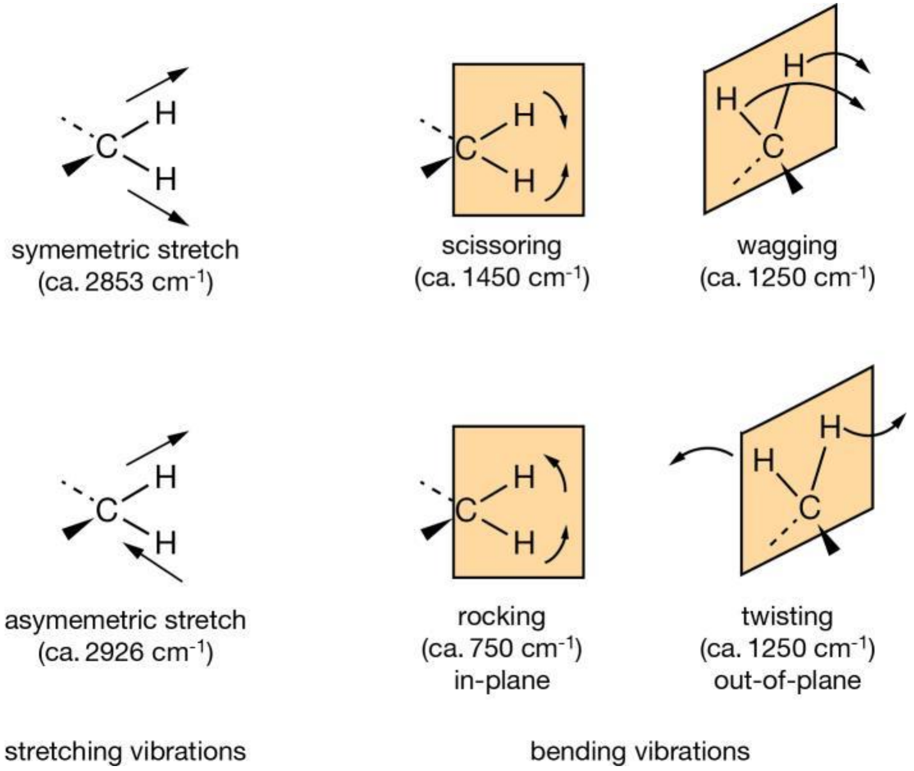
Molecular spectra

Molecules too absorb & emit photons of characteristic energy or frequency, by changing their vibrational modes.

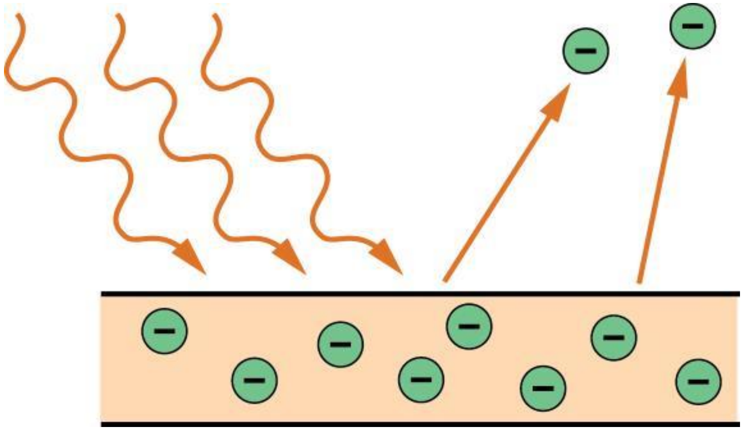
Spectroscopy – e.g

- to monitor car exhausts
- to find the rotation rate of stars
- to analyse pigments in a painting
- to identify forensic substances
- to map a patient's internal organs

Greenhouse effect



Photoelectric effect

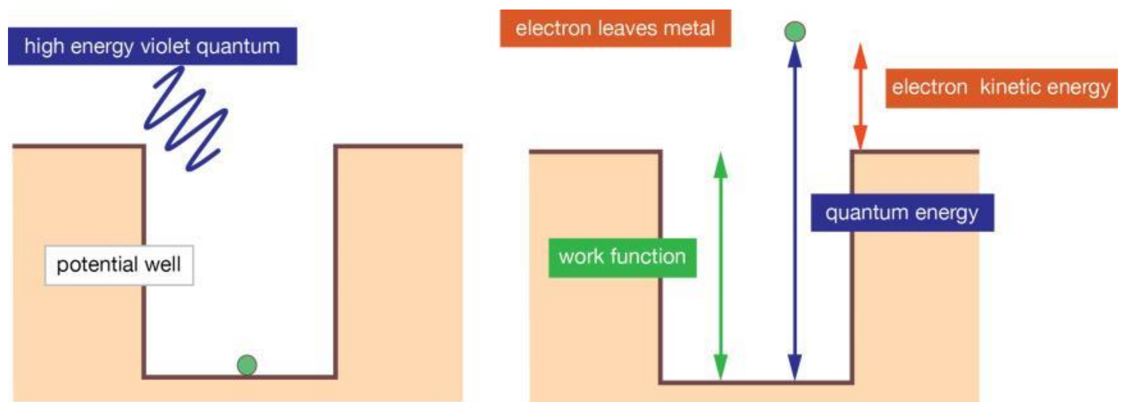


Observations

- There is a threshold frequency, below which no emission occurs.
- The maximum E_k of the electrons is independent of light intensity.
- Photoelectric current is proportional to light intensity.

Photoelectric effect

Energy of incident photon $E = hf$



The photon's energy can do two things:

- enable an electron to escape the metal surface (work function, ϕ).
- give the free electron E_k.

$$hf = j + E_{\mathrm{k\,max}}$$

Photon flux

Calculate the number of quanta of radiation being emitted by a light source.

Consider a green 100 W lamp. For green light the wavelength is about 6×10^{-7} m and so:

Energy of a photon = $E = hf = hc / \lambda = 3.3 \times 10^{-19}$ J

The number of quanta emitted per second by the light,

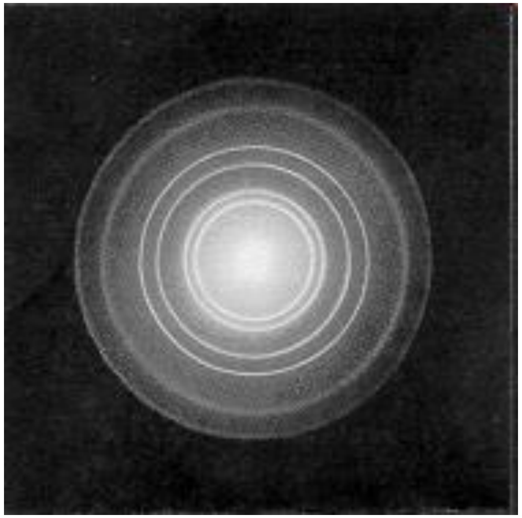
$$N = \frac{100\text{Js}^{-1}}{3.3\times10^{-19}\,\text{J}} = 3\times10^{20}\,\text{s}^{-1}$$

Photons from LEDs

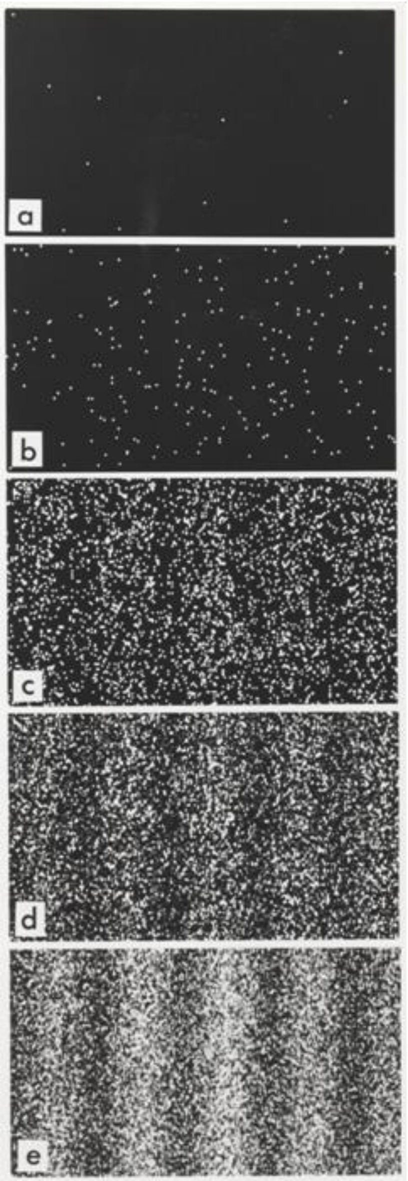
Energy of electrons releases a visible photons from the semi-conducting material.

$$eV = hf = \frac{hc}{\lambda}$$

Electron diffraction



polycrystalline target
(a 2-dimensional grating)



de Broglie

$$\lambda = \frac{h}{m_e v} = \frac{h}{p}$$

The double-slit experiment with increasing numbers of electrons:
a: 10 electrons
b: 200
c: 6000
d: 40 000
e: 140 000

Quantum behaviour

- **not** particle behaviour
- **not** wave behaviour

Young's double slit with photons: Wave calculations give the right answers for where there are bright and dark fringes. Physicists use the wave calculation but don't think of light simply as waves.

Phase is an intrinsic property of quantum objects, so interference can result from path differences. [analytic tool is 'phasor' $f = \frac{E}{h}$]

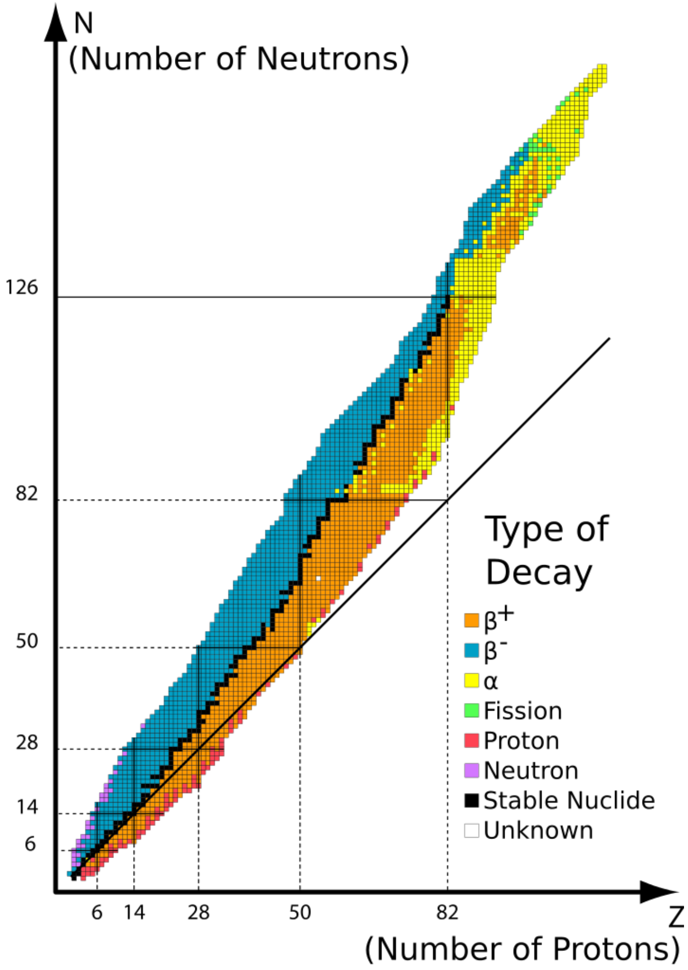
Practice questions

TAP sheets

- *Quanta*
- *Photoelectric effect questions*
- *De Broglie equation: worked examples*
- *Electron diffraction question*

Stability of nuclei

Carbon-12 is stable.
Carbon-14 is radioactive, decaying to nitrogen-14



Darker isotopes shown here are stable.

Building nuclei

Discrete energy levels inside the nucleus

'Fermions' are particles that cannot share the same quantum state.
(They obey the Pauli exclusion principle.)

Protons & neutrons are both are fermions. Two protons cannot share same quantum state. Two neutrons cannot share same quantum state. A proton and neutron *can* share same quantum state. This is what tends to keep their numbers in nuclei roughly equal.

But more massive nuclei (with larger numbers of protons repelling each other) have progressively more neutrons than protons. stable nuclei include iron-56 (30n, 26p), lead-206 (124n, 82p)

Stability depends on energy

- Gravitational forces hold the solar system together.
- Electrical forces hold atoms together. It takes energy to pull them apart.

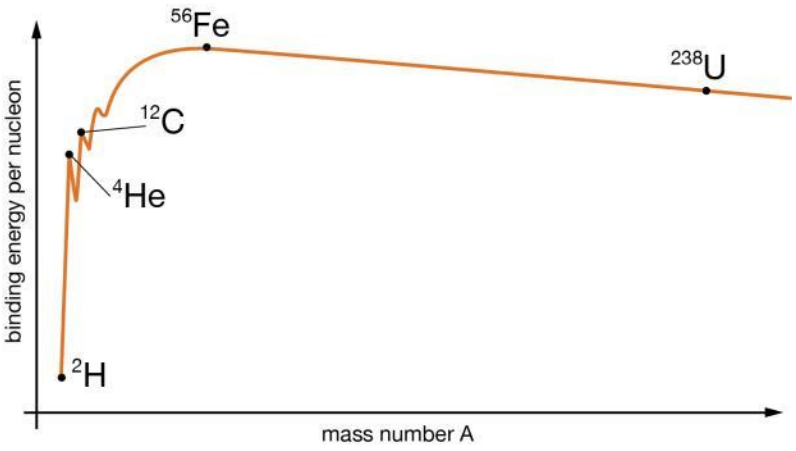
In each case the energy of the bound system is less than all the pieces if pulled apart. (Work must be done on the system.)

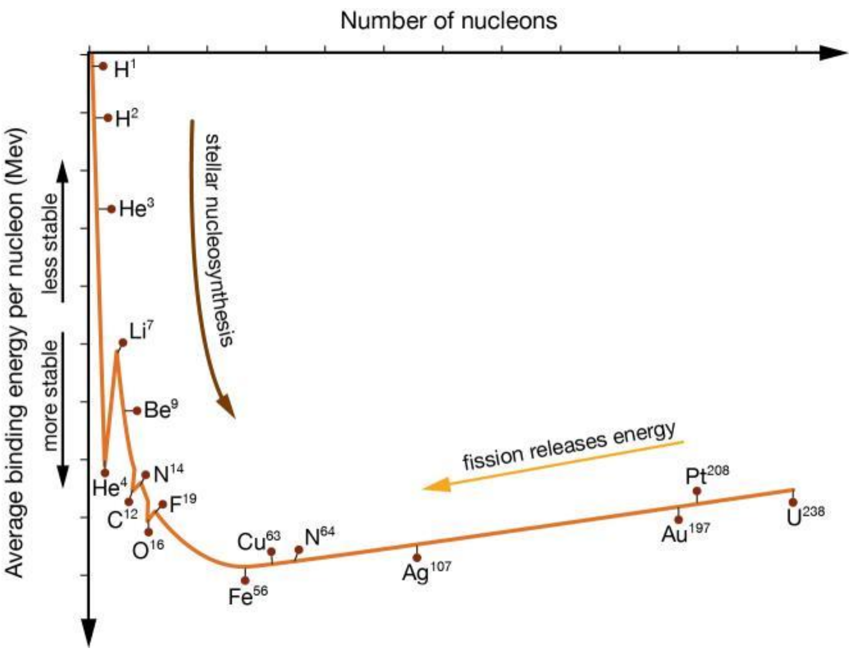
The energy of a bound nucleus must be less than the energy of its protons and neutrons taken separately.

Mass defect: mass of product(s) is less than mass of reactants

Einstein: particles have rest energy $E_{\text{rest}} = mc^2$

Binding energy per nucleon



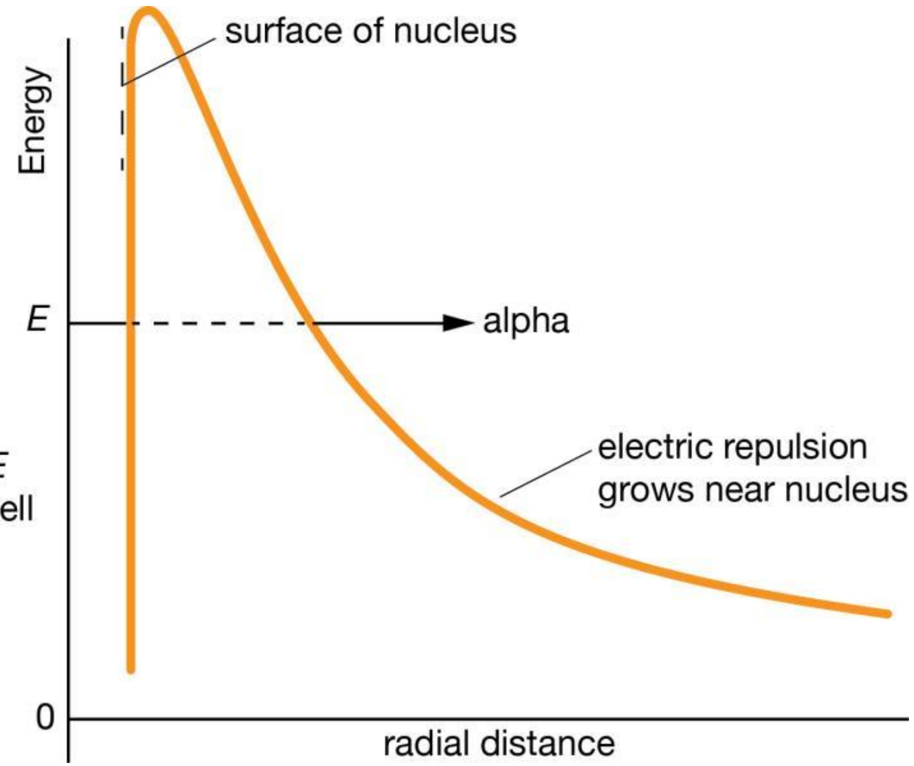


The binding energy for nuclei is a million times greater than for atoms.

unit of energy: MeV

Quantum tunnelling

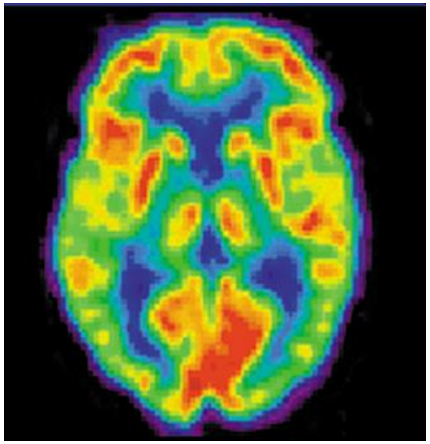
Potential barrier around a uranium nucleus presented to an alpha particle.
The central well is due to the average nuclear attraction of all the nucleons and the hill is due to the electric repulsion of the protons.
Alpha particles with energy *E* trapped inside the nuclear well may still escape to become alpha rays, by quantum mechanically tunnelling through the barrier.



Practice questions 2

TAP *Change in energy, Change in mass*

PET scans



Positron emission tomography

- inject into label bloodstream a radio-isotope (e.g. ^{15}O) which emits a positron (e^+) when proton becomes a neutron.
- when e^+ collides with a nearby e^-, they annihilate, producing a pair of γ photons travelling in opposite directions.
- detectors and computer identify *almost* simultaneous γ photons, using the small time difference to locate source.

Matter and anti-matter

- same mass & spin; all other quantum properties opposite (charge, etc.)
- predicted by Dirac equation (1928). Positron discovered in cosmic rays (1932). Experimentally produced anti-proton (1955), anti-neutron (1956).

Particle physics

Aim: Find rules for particles interactions and transformations.

Method: Collide particles at high energy to produce interactions and transformations, then track and analyse resulting particles. Particle creation and annihilation follows $E = mc^2$.

SLAC (90 GeV) electrons + positrons

CERN LEP 1989-2000 (209 GeV) electrons + positrons

Fermilab Tevatron (1.96 TeV) protons + antiprotons

CERN LHC (2008-) proton + proton (7TeV) or lead nuclei (574TeV)

Many hundreds of kinds of particles are produced.

In 1964 Gell-Mann & Zweig independently propose the quark model to explain the ‘particle zoo’

What the world is made from

Generation	LEPTONS	charge	rest energy	QUARKS	charge	rest energy
1	electron neutrino	-1 0	0.511 MeV ~0.3 eV	up down	+2/3 -1/3	2.4 MeV 4.8 MeV
2	muon muon-neutrino	-1 0	106 MeV	strange charm	-1/3 +2/3	104 MeV 1.27 GeV
3	tau tau-neutrino	-1 0	1780 MeV	bottom top	-/13 +2/3	4.2 GeV 171.2 GeV

Families of particles

hadrons – made of quarks

- baryons – heavy particles made of 3 quarks
- mesons – medium mass particles, made of quark-antiquark pair

leptons – light particles e.g. electron, neutrino

Beta decay

$$^{14}_{6}\mathrm{C} \rightarrow ^{14}_{7}\mathrm{N} + \beta^{-} + \overline{\upsilon}$$

$$\mathrm{n} \rightarrow \mathrm{p} + \beta^{-} + \overline{\upsilon}$$

$$udd \rightarrow uud + \beta^{-} + \overline{\upsilon}$$

with gluons mediating quark interactions

Bosons: carriers of interactions

interaction	force carrier	electric charge	rest energy	explains
electromagnetism	photon	0	0	everyday interactions including all chemistry
weak interaction	Z^0 W^+ W^-	0 +1 -1	93 GeV 81 GeV 81 GeV	β decay, other particle transformations
strong interaction	8 different 'colour combinations' of gluons	0	0	what holds nucleons & mesons together
gravity	'graviton'	0	0	conjectured but not detected

THANK YOU