Lecture B1

RADIATION and PARTICLES

Detlev Gotta

Institut für Kernphysik, Forschungszentrum Jülich / Universität zu Köln

“Autumn Lectures” – Nuclear and Medical Physics

Tbilisi, Georgian Technical University (GTU)

October 15, 2013

OVERVIEW LECTURE 1

REMARKS ON RADIATION AND PARTICLES

HOW TO DETECT ?

HOW TO MEASURE ?

UNITS, CONSTANTS, RELATIONS, KINEMATICS

PARTICLES

particle detector registration

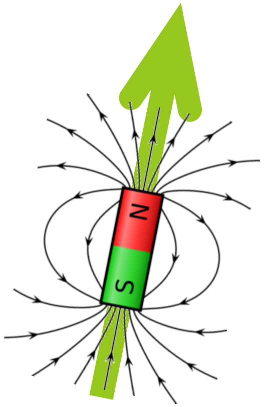
Light

Heavy

PARTICLES

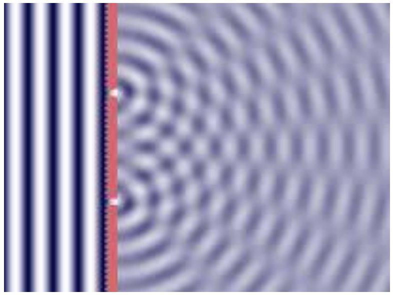
What characterizes a particle?

mass		***M***
charge		***Q***
Spin	***intrinsic angular momentum***	***S*** ⇔ ***magnetic moment***
life time		τ_0
shape	***for non elementary particles***	$<r^2>$

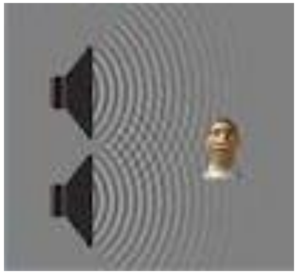


RADIATION

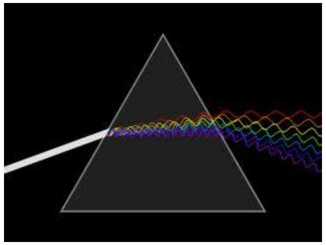
fluid

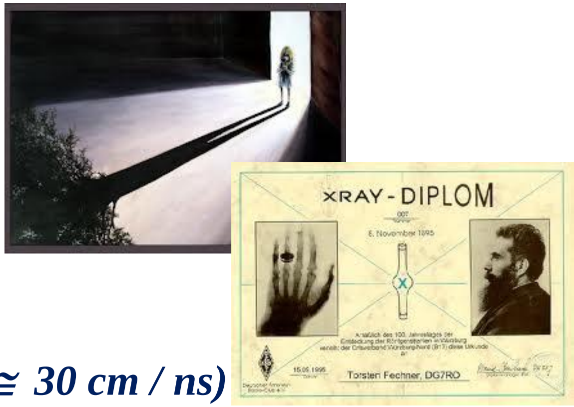


gas



„light“





XRAY - DIPLOM

8. November 1895

15.06.1995

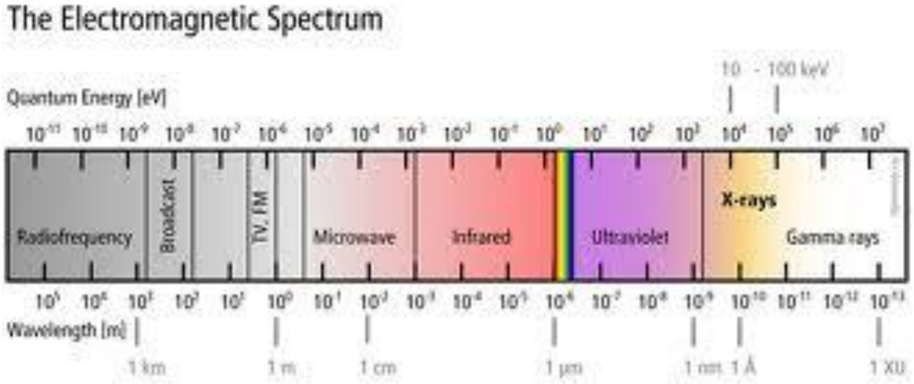
Torsten Fechner, DG7RO

fundamental constant: c = speed of light in vacuum (≅ 30 cm / ns)

RADIATION

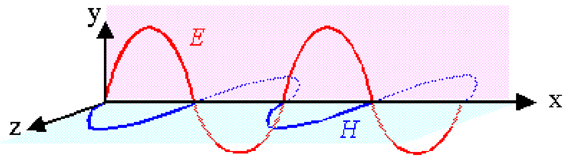
What characterizes waves?

ability to interfere



wave length λ

frequency ν

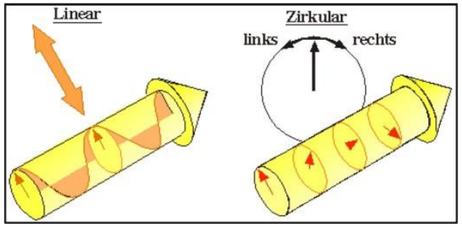


wave propagation velocity in vacuum $c = \lambda \nu$

“ “ “ in medium $c' = \lambda' \nu < c$

index of refaction $n = c / c'$

one more degree of freedom: spin 1 ***m = ±1, <u>no</u> m = 0***

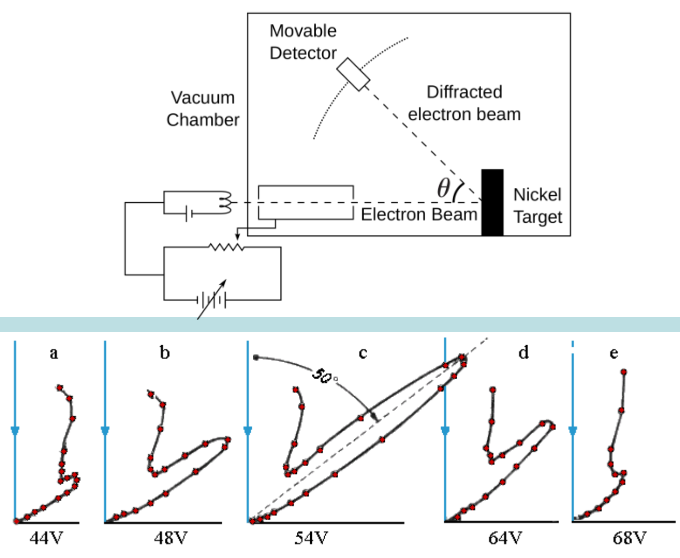


MATTER or WAVES?

particles, e.g. electrons, are diffracted

54 eV electrons on a Ni crystal

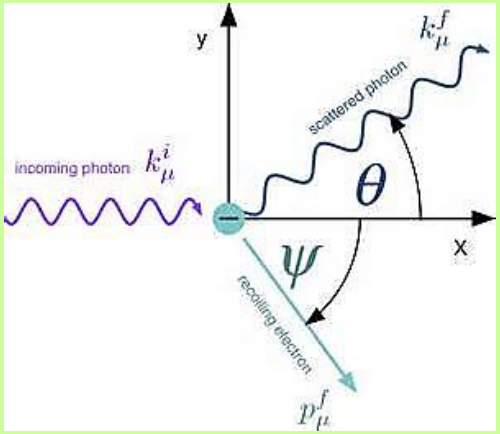
Davisson-Germer (1927)



light – photons – play billiard

X-rays on carbon

Compton (1922)



ANSWER: BOTH! I

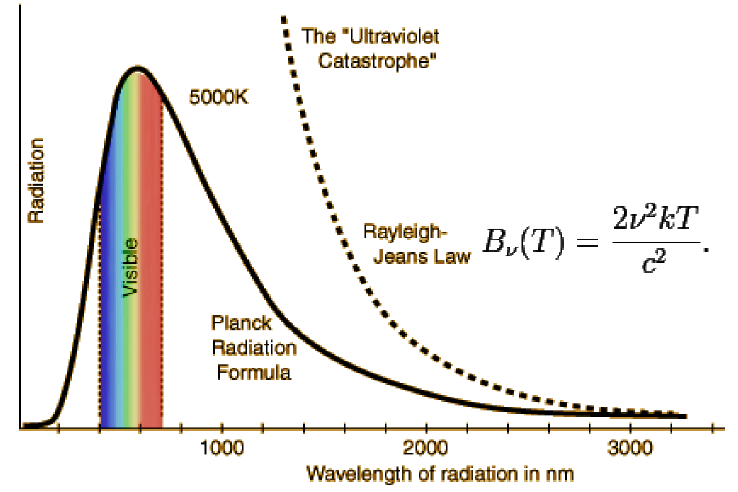
Planck radiation law *1900*

$$B_\nu(T) = \frac{2h}{c^3}\cdot\frac{\nu^3}{e^{h\nu/kT}-1}$$

energy density of blackbody radiation

h: Planck constant

quantized quantity is action $S = \int E(t)dt$ [J·s]

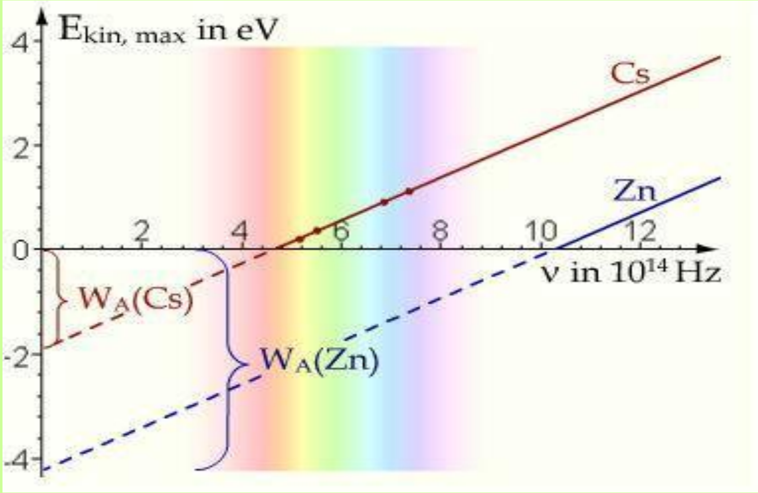


Einstein equation for photo effect *1905*

$$h\nu = W_A + E_{kin,electron}$$

$E_{photon} = h\nu$ *„light particle“*

$h = E \cdot T$ *minimal action*



ANSWER: BOTH! II

particles are waves de Broglie 1922

special relativity $E = \gamma \cdot m_0 \beta c^2$

$p = \gamma \cdot m_0 \beta c$

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

photo effect $E = h\nu = hc/\lambda$

uncertainty relation Heisenberg 1927

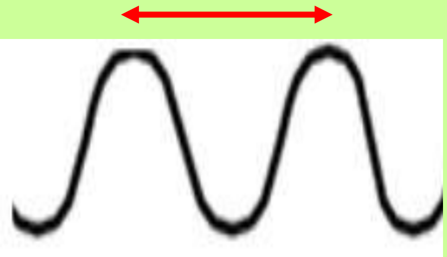
$measuring\ time \rightarrow 0$
$energy\ information \rightarrow \infty$

$$\Delta E \cdot \Delta t \approx \hbar/2$$

$$\Delta x \cdot \Delta p \approx \hbar$$

$$\Delta J \cdot \Delta \varphi \approx \hbar$$

$$T = {}^{1}/_{\nu}$$

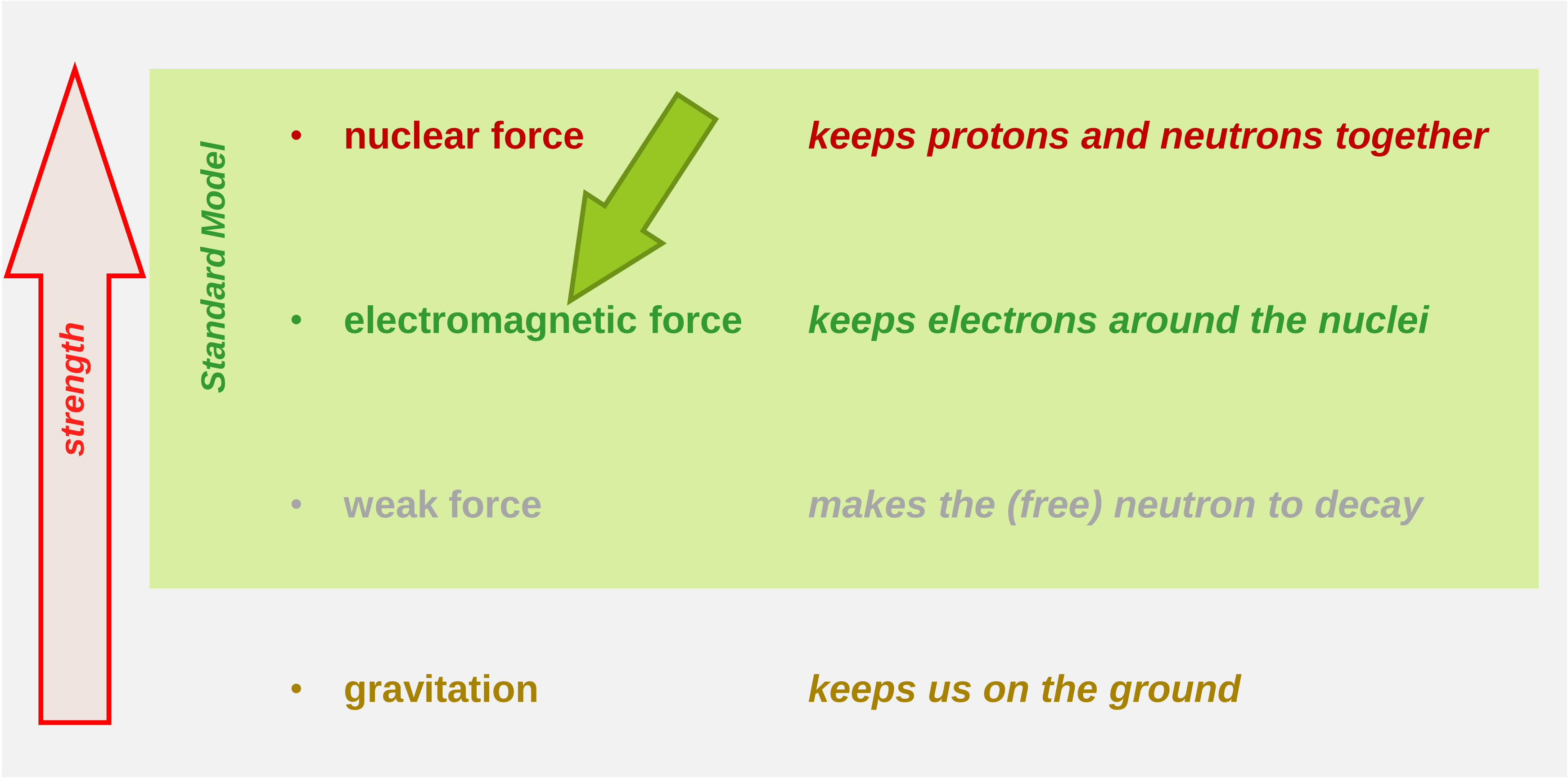


$$\lambda \cdot \nu = c$$

$$\Delta t \cdot \Delta E \approx \frac{h}{2}$$

HOW TO DETECT ?

known forces – which one can be used ?



nuclear force	*keeps protons and neutrons together*
electromagnetic force	*keeps electrons around the nuclei*
weak force	*makes the (free) neutron to decay*
gravitation	*keeps us on the ground*

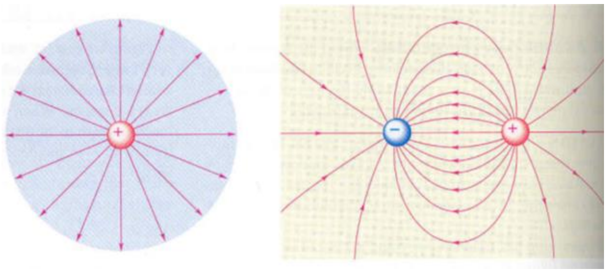
ELECTROMAGNETIC FORCE

a force is mediated

classical picture

by field around a source

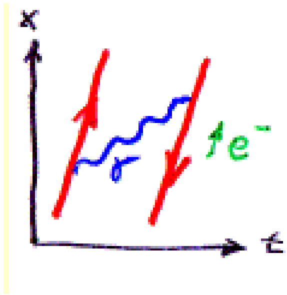
$$F_{Coulomb} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{Q_1 Q_2}{r^2}$$



quantum world

field quanta = particles

„light“ particles = photons γ

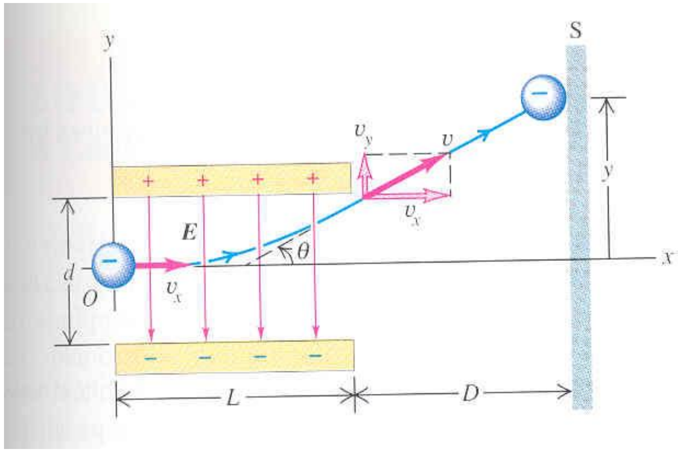


electromagnetic radiation = E and B fields interact with electric charges

INTERACTION WITH ELECTRIC CHARGE

- **electric field**

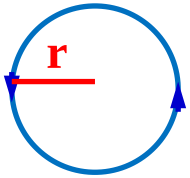
$$\vec{F} = m\ddot{\vec{x}} = Q \cdot \vec{E}$$



$$\boxed{\Rightarrow \quad \frac{Q}{M}}$$

- **magnetic field**

$$\vec{F} = m\ddot{\vec{x}} = Q \cdot \left(\vec{v} \times \vec{B}\right)$$



B = const.

$\Rightarrow$ *circular motion*

B $\perp$ *plane of projection*

$$\omega = \frac{Q}{M} B \qquad \omega = \frac{2\pi}{T}$$

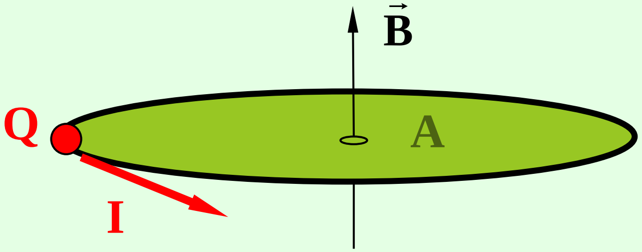
$$\boxed{\Rightarrow \quad p}$$

$$mv^2 / r = Q \cdot v \cdot B$$

$$p = Q \cdot B \cdot r$$

INTERACTION WITH MAGNETIC MOMENT

„magneto-mechanical“ view of magnetic moment



magnetic dipole is produced by

circular current $I = \frac{Q\cdot\omega}{2\pi}$

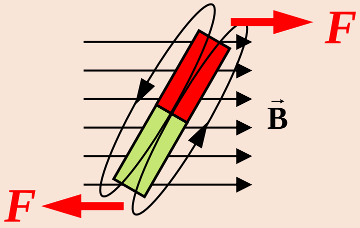
magnetic moment $\vec{\mu} \equiv I \cdot A = \frac{Q}{m}\cdot\vec{L}$

subatomic particles: possible without any mechanical analogon (extension)

Bohr magneton	$\mu_B = \frac{e\hbar}{2m_e}$	$\mu_e = -\,g_e\cdot\mu_B\cdot\frac{S}{\hbar}$	$g_e = 2 + 2\cdot 10^{-6}$	*elementary particle*
nuclear magneton	$\mu_N = \frac{e\hbar}{2m_p}$	$\mu_p = \quad g_p\cdot\mu_B\cdot\frac{S}{\hbar}$	$g_p = 5.6$	*not an elementary particle*

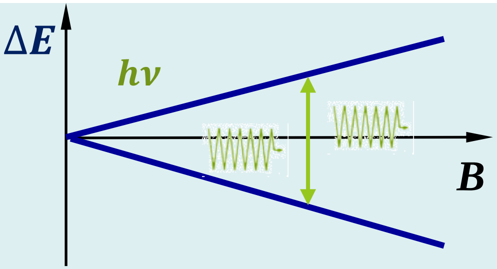
torque $\vec{M} = \vec{\mu}\times\vec{B}$

change in units of $g\cdot\mu_B/g\cdot\mu_N$



interaction energy

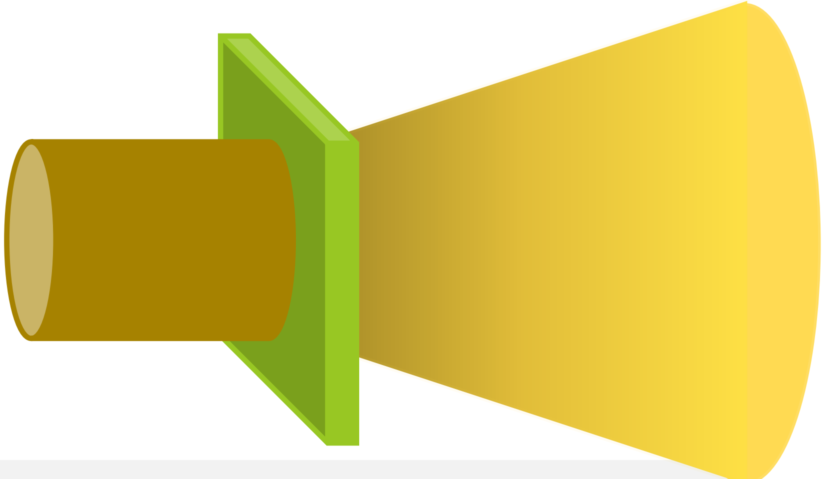
$\Delta E = \vec{\mu}\cdot\vec{B}$

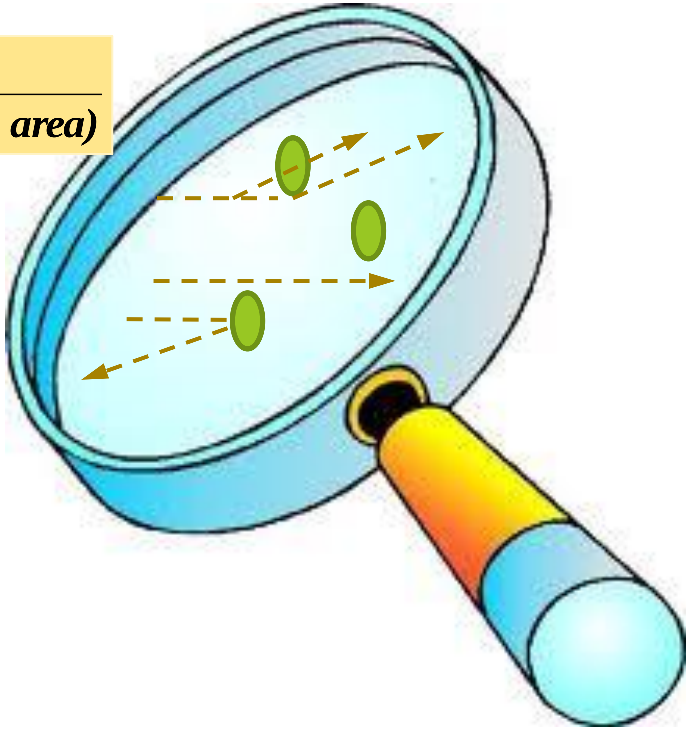


HOW TO MEASURE: CROSS SECTION I

measures the probability of a reaction

$$\sigma = \frac{\textit{reactions / time interval}}{(\textit{incoming particles / time interval}) \times (\textit{target particles / area})}$$





F = target area ∩ beam cross section [cm^2]

particle $$\sigma = \frac{N}{N_0} \cdot \frac{1}{n/F}$$ *N_0 incoming particles in beam*

wave $$\sigma = \frac{I}{I_0} \cdot \frac{1}{n/F}$$ *intensity I_0 of incoming radiation*

ρ = target density [g / cm^3]
$n^{\square}$ = $n / F \times d$
= $\rho \cdot (N_A / A)$ [particles / cm^3]
N_A = Avogadro constant
A = mass number [g]

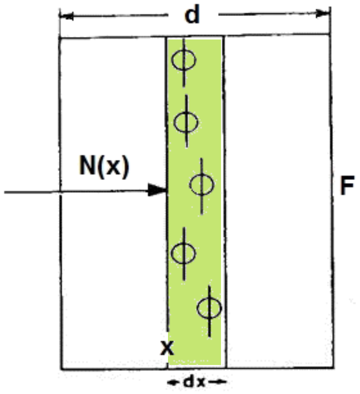
CROSS SECTION II

reaction rate

„thin“ target *differential notation (N → dN)*

$$-\ dN\,(x) \ = \ N(x)\cdot \left(\rho\cdot\frac{N_A}{A}\right)\cdot\sigma\cdot dx$$

setup *„physics”*



„thick“ target *integration over target thickness* d

$N\,(d) \ = \ N(0)\ \cdot\ e^{-\rho\frac{N_A}{A}\sigma\cdot d}$ *= number of not interacting particles (transmission)*

$R\,(d) \ = \ N(0)\cdot(\,1\ -\ e^{-\rho\frac{N_A}{A}\sigma\cdot d})$ *= number of interacting particles (reaction/absorption)*

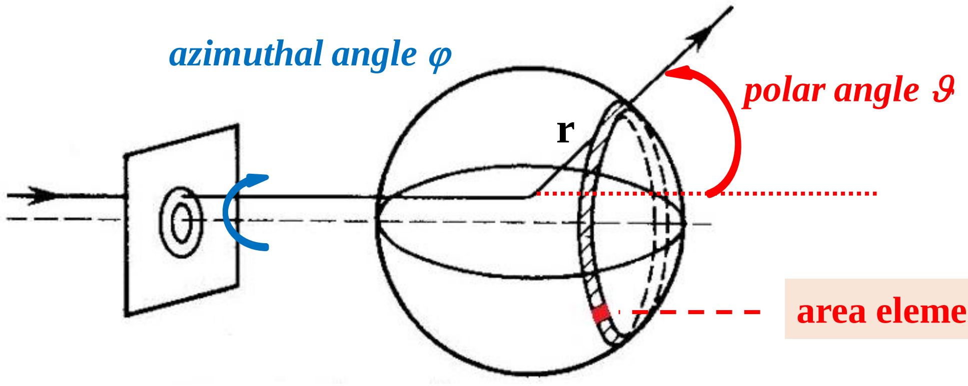
linear extinction coefficient $\mu \equiv (\rho\cdot\frac{N_A}{A})\cdot\sigma$ **ρ: status of target A**

mass absorption coefficient $\lambda^{-1} \equiv \frac{\mu}{\varrho} = \frac{N_A}{A}\cdot\sigma$ **independent of state of aggregation of target A**

mixture/compound **total cross section** $\sigma_{\text{total}}(E) = \Sigma\,\sigma_{\text{partial}}(E)$ **[1 barn = 10^{-24} cm^2]**

CROSS SECTION III

differential cross section includes angular information of scattering



solid angle element

$\Delta\Omega \equiv \Delta A / r^2$ [steradian (sr)]

area element $\Delta A = r\,\Delta\vartheta \cdot r \sin\vartheta\,\Delta\varphi$

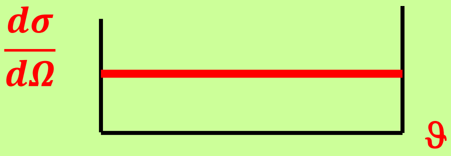
azimuthal symmetry $\Delta\Omega = 2\pi \sin\vartheta\,\Delta\vartheta$ *φ integration*

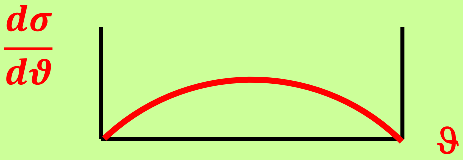
full sphere $\Omega = 4\pi r^2 / r^2 = 4\pi$ („4π“ detector)

fraction of full solid angle $\Delta\Omega / 4\pi$

$$\frac{d\sigma}{d\Omega} = \frac{1}{2\pi \cdot \sin\vartheta} \cdot \frac{d\sigma}{d\vartheta}$$

$\frac{d\sigma}{d\Omega} = const.$ **isotropy in ϑ**





UNITS

		atoms		nuclei or particles
length		1 nm = 10^{-9} m		1 fm = 10^{-15} m (= 1 Fm)
	- Bohr radius	*$\approx 0.5\ 10^{-10}$ m = 0.05 nm*		
	- proton „radius“			*$\approx 0.8\ 10^{-15}$ m = 0.8 fm*
energy		eV		MeV
	- binding energy	*- 13.6 eV $\cdot Z^2 / n^2$*		*$\approx$ 8 MeV / nucleon.*
	- visible light	*1 – 2 eV*		*γ – rays up a few MeV*
	- X-rays	*up to $\approx$ 100 keV*		
momentum		eV/c		MeV/c
time		1 fs = 10^{-15} s		1 ys = 10^{-24} s
	- life time	*2p hole in K atom $\approx$ 6 fs*		*Δ baryon 6$\cdot 10^{-24}$ s*
mass		a.m.u. $\equiv$ m(^{12}C)/12		MeV/c^2
	rest mass m_0	*$\approx$ A $\cdot$ a.m.u.*	*- a.m.u.*	*931.5* MeV/c^2 *= 1.66$\cdot 10^{-27}$ kg*
			- proton	*938.3* MeV/c^2 *$\approx$ 1 a.m.u.*
			- neutron	*939.6* MeV/c^2 *$\approx$ 1 a.m.u*
			- electron	*0.511* MeV/c^2 *= 9$\cdot 10^{-31}$kg $\approx$ 1/1823 a.m.u*
angular momentum (Spin)		j = 0,1/2,1,3/2, ... $\hbar$		**[j]=[E·t]**
magnetic moment		$\mu_B = 5.8 \cdot 10^{-11}$ MeV$\cdot$T^{-1}		$\mu_N = 3.2 \cdot 10^{-14}$ MeV$\cdot$T^{-1}
cross section		σ		*10^{-24} cm^2 = 1 barn (b)*
				1 a. u. = r_B^2

CONSTANTS

speed of light ***definition!***	c	$\equiv$ 299 792 458 m/s	$\approx$ 0.3 cm/ns
elementary charge (±)	e	= $1.6\cdot10^{-19}$ C	
Avogadro constant	N_A	= $6.02\cdot10^{23}$ / mol	
Planck constant	h	= $6.6\cdot10^{-34}$ J·s	
	$\hbar$	= $h/2\pi$	analogue ƛ, …
	$\hbar$	= $6.582\cdot10^{-22}$ MeV·s	
fine-structure constant	α	= $e^2/4\pi\varepsilon_o\hbar c$	= 1/137
classical electron radius	r_e	= $e^2/4\pi\varepsilon_o m_e c^2$ = $\alpha\,\hbar c\; m_e c^2$	= 2.82 fm
conversion constant	$\hbar c$	= 197 MeV·fm ($\hbar=h/2\pi$), analogue ƛ, …	
conversion constant	hc	= 12.4 keV$\cdot10^{-10}$ m	

RELATIONS

wave propagation	$c = \lambda\nu$	
Photon energy	$E = h\nu = \hbar\,\omega$	
uncertainty relation	$\Delta p \cdot \Delta x \geq \hbar$	$\Delta E \cdot \Delta t \geq \hbar$
life time $t \Leftrightarrow \Delta E \equiv \Gamma$	$\Gamma \cdot \tau = \hbar/2$	MeV·s
Bohr formula	$E_B = -mc^2 \cdot \frac{(Z\alpha)^2}{2n^2}$	$Ryd = m_e c^2 \cdot \frac{\alpha^2}{2} = 13.6\ eV$
Bohr radius	$r_B = \frac{\hbar c}{\alpha m_e c^2} mc^2 = r_e \alpha^{-2}$	$= 0.53 \cdot 10^{-10}\ m$
Virial theorem	$2 \cdot \langle T_{kin} \rangle = n \cdot \langle V_{tot} \rangle$	$\langle \dots \rangle\ average\ of$ ...
count rate	$N = N_{in} \cdot \rho d \frac{N_A}{A} \cdot \sigma$	

RELATIVISTIC KINEMATICS

	massive particles		el.-mag. radiation	
total energy	$E_{total} = \sqrt{p^2c^2 + m_0^2c^4}$ $= \gamma\, m_0 c^2$		$E_{total} = pc$ $= h\nu$	*h Planck constant* *= minimal action*
kinetic energy	$E_{kin} = E_{total} - m_0 c^2$		$= E_{kin}$	
momentum	$p = \gamma\, m_0 c \cdot \beta$		$p = \frac{E}{c}$	
rest mass	$m_0 \neq 0$	*range in matter*	$= 0$	*attenuation in matter*
charge	$Q \neq 0$	*deflection in el.-mag fields*	$= 0$	*no deflection*
life time	$\tau = \gamma\tau_0$	*decay length **l = v τ***	$= \infty$	

relativistic factor

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}, \qquad \beta = \frac{v}{c} \qquad \lim \gamma \xrightarrow[v \to c]{} \infty$$