Particle and Radiation Detectors: Advances & Applications

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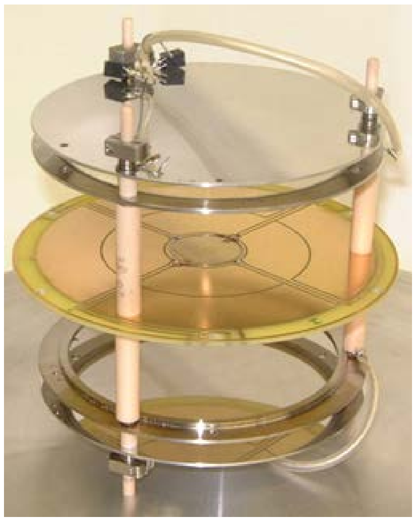
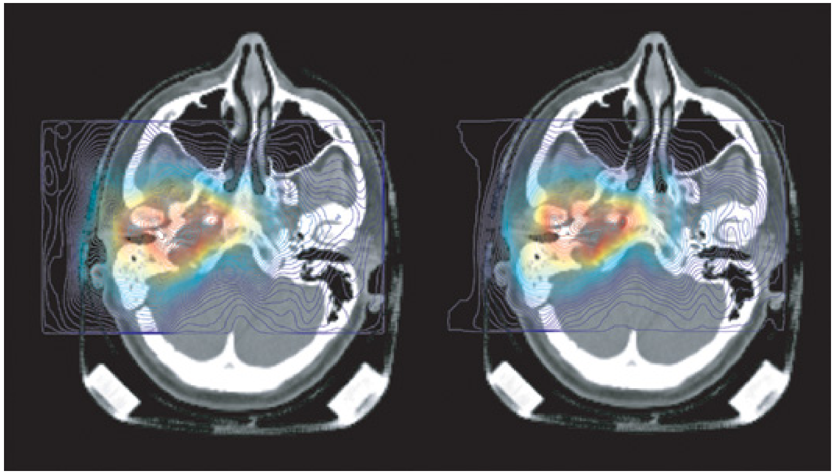
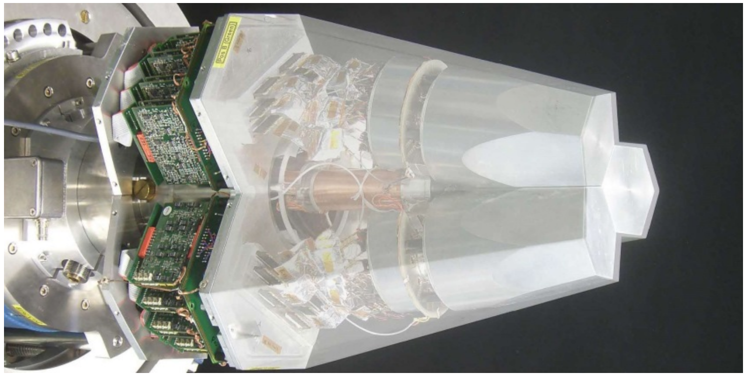
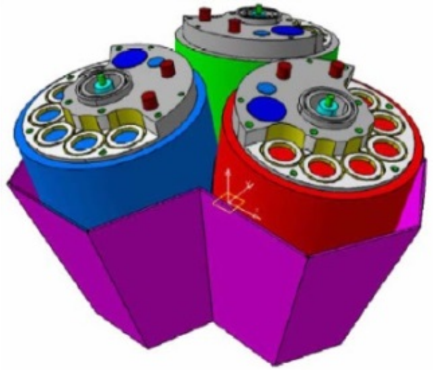




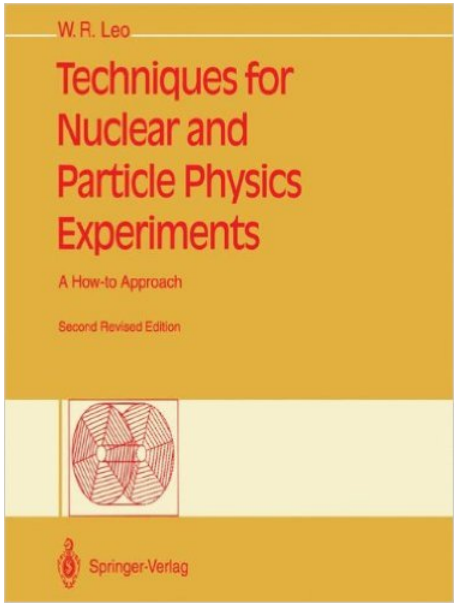




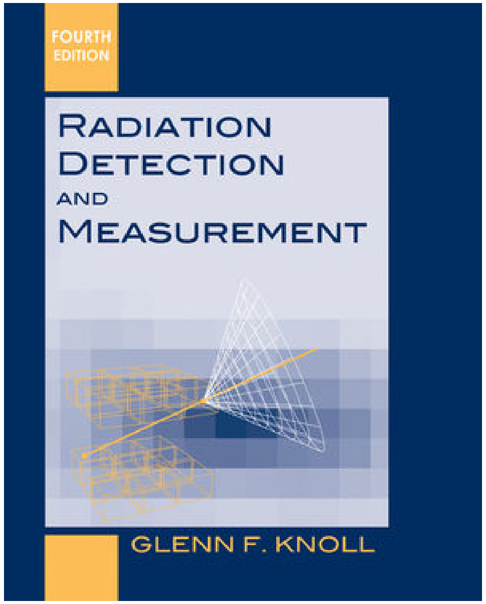
Tentative outline of detector lecture

- **Charged particle interaction in matter**
  - relevant formulas
  - Bethe-Bloch formula
  - interaction of β-particles in matter
  - Bremsstrahlung
  - Synchrotron radiation
- **Interaction of gamma-rays in matter**
  - photoelectric effect
  - Compton scattering
  - e^+e^- pair production
- **Semiconductor detectors**
  - bond model for semiconductors
  - doping: n- and p-type silicon
  - Silicon surface barrier detector
  - micro-strip detector
  - Germanium detector
- **Segmented detectors**
  - Doppler effect
  - Euroball, Miniball, AGATA
- **Electronics**
  - signal processing
  - constant fraction discriminator
  - coincidences
- **Gas detectors**
  - ionization detectors
  - ionization chamber
  - proportional counter
  - multi-wire proportional chamber
  - time projection chamber
  - Geiger-Müller counter
- **Scintillation detectors**
  - organic and inorganic scintillators
  - Liouville's theorem
  - photomultiplier tube
  - neutron detector
- **Neutral particles**
  - neutrons
  - neutrino
- **Imaging**

Literature



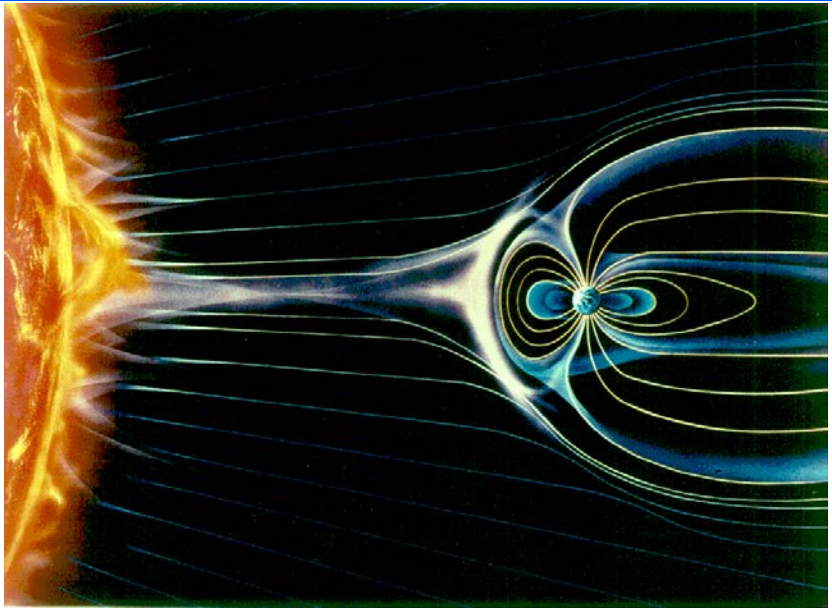
❖ Recommended Textbook



❖ Recommended Textbook

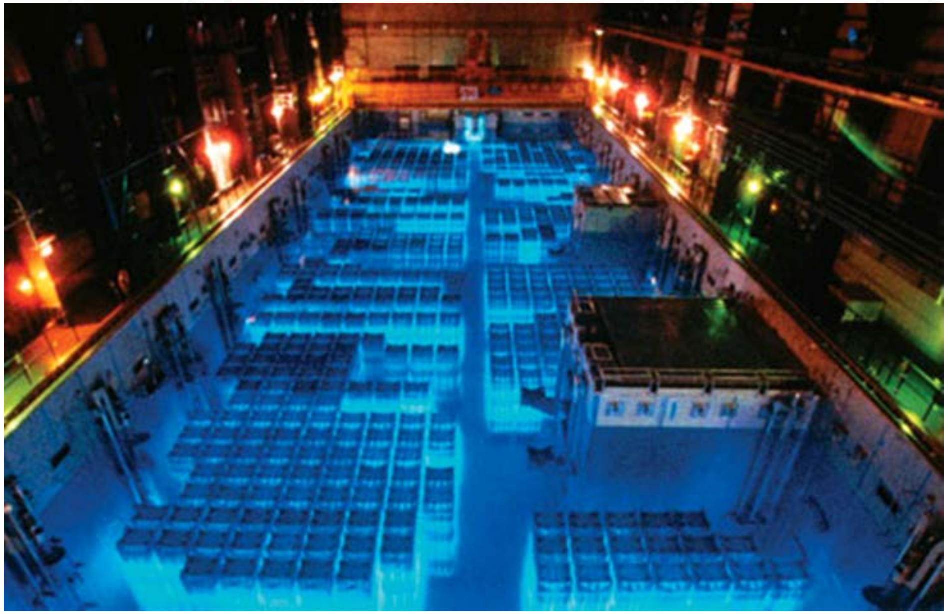
Particle Interaction with Matter

Aurora Borealis



Ionization

Particle Interaction with Matter

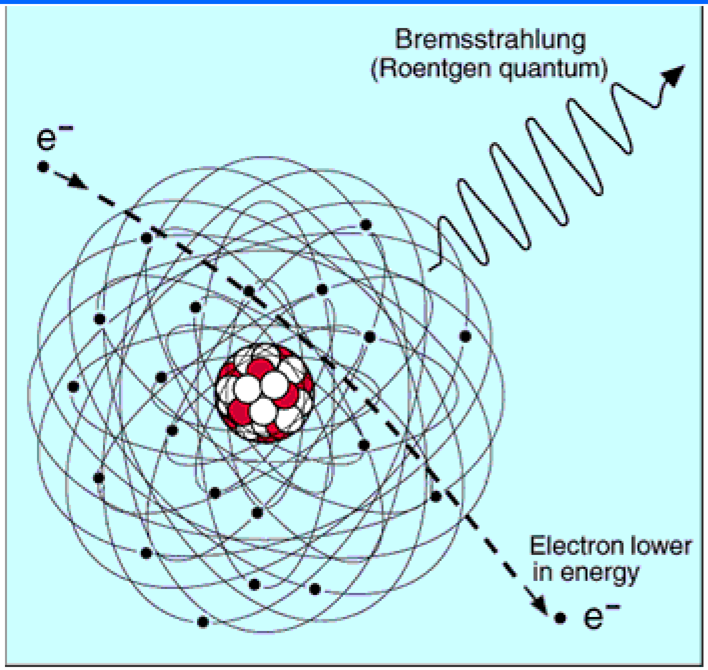


Characteristic glow from a reactor

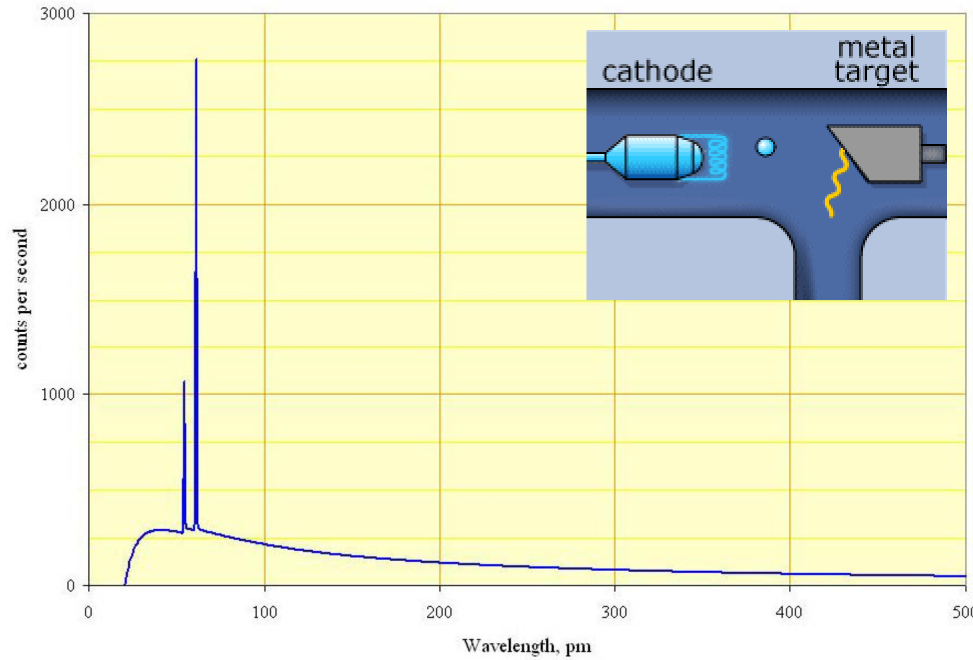
Cherenkov Light

Cherenkov radiation is an effect similar to sonic booms when the plane exceeds the velocity of sound

Particle Interaction with Matter



Bremsstrahlung or ‘braking radiation’



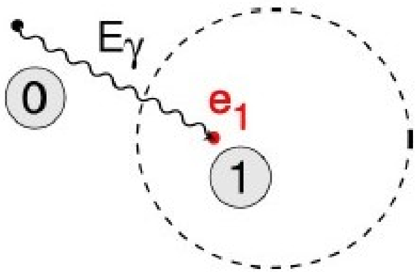
Spectrum of the X-rays emitted by an X-ray tube with a rhodium target, operated at 60 kV. The continuous curve is due to bremsstrahlung, and the spikes are characteristic K lines for rhodium.

Bremsstrahlung

Interaction of gamma rays with matter

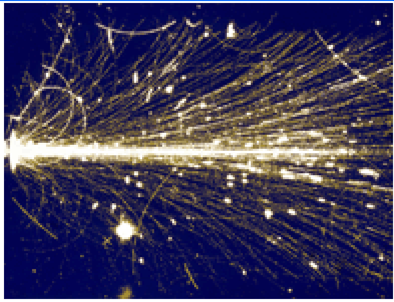
~ 100 keV | ~1 MeV | ~ 10 MeV | γ-ray energy

Photoelectric



Isolated hits

Probability of interaction depth



Particles interact differently with matter. Important for detectors is the energy loss per path length. The total energy loss per path length is the sum of all contributions.

$$-\left(\frac{dE}{dx}\right)_{tot} = -\left(\frac{dE}{dx}\right)_{coll} - \left(\frac{dE}{dx}\right)_{rad} - \left(\frac{dE}{dx}\right)_{photoeff} - \left(\frac{dE}{dx}\right)_{compton} - \left(\frac{dE}{dx}\right)_{pair} - \left(\frac{dE}{dx}\right)_{hadron} \cdots$$

Depending on the particle type, the particle energy and the material some processes dominate, other do not occur. For instance only charged particles will interact with electrons of atoms and produce ionization, etc.

Measurement Principles

A measurement requires an interaction of the particle with the material of the detector. The interaction provokes two effects:

1st Creation of a detectable signal, e.g.
ionization → charges
excitation → scintillation
excitation of phonons → heat

2nd Alternation of the particles properties, e.g.
energy loss
change of trajectory due to scattering
absorption

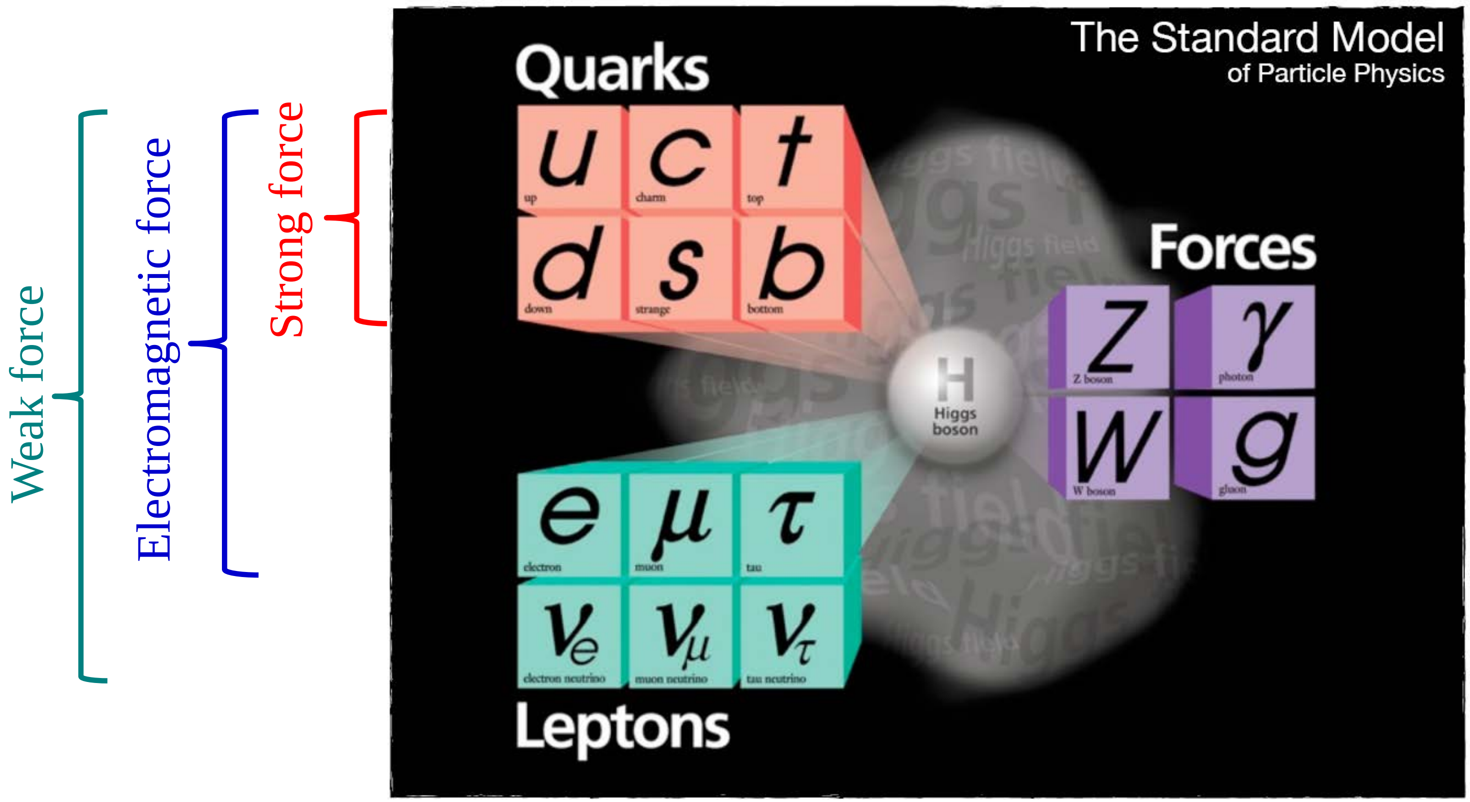
unwanted side effects. They need to be as small as possible and well understood.

Measurement Principles

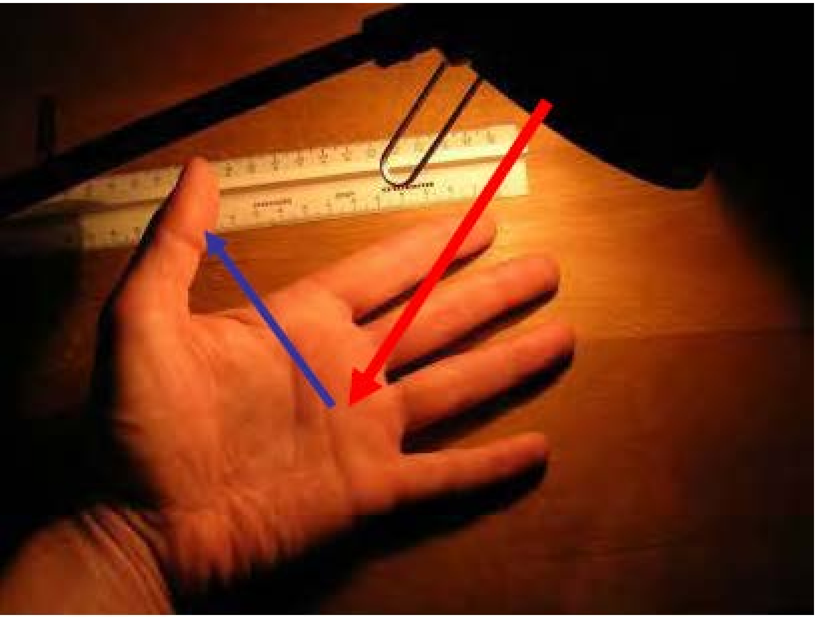
A particle detector is an instrument to measure one or more properties of a particle …

Properties of a particle		Type of detection principle:
- position and direction	$x, \vec{x}$	position and tracking
- momentum	$\lvert\vec{p}\rvert$	tracking in a magnetic field
- energy	E	calorimetry
- mass	m	spectroscopy and PID
- velocity	β	Cherenkov radiation or time of flight
- transition radiation	γ	TRD
- spin, lifetime		

What is a Particle?



How do we see Particles?



A light bulb shines on a hand and the different reflections make the fine structure visible.
With a magnifying glass or microscope more details can be seen, but there is a fundamental limit:
The wavelength of the light (1/1000 mm) determines the size of the resolvable objects.

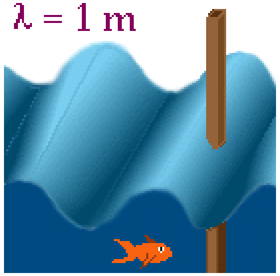
available wavelength

→ electromagnetic waves $E = \frac{hc}{\lambda}$

LW	3000 m	
MW	300 m	
KW	30 m	
UKW	3 m	
GPS	0.3 m	
Infrared	10^{-6} m	
light	$5\cdot10^{-7}$ m	2 eV
UV	10^{-7} m	10 eV
X-ray	10^{-10} m	10^{4} eV
γ-ray	10^{-12} m	10^{6} eV

light bulb → accelerator
magnifying glass or microscope → detector

Energy, Wavelength and Resolution



wavelength versus resolution

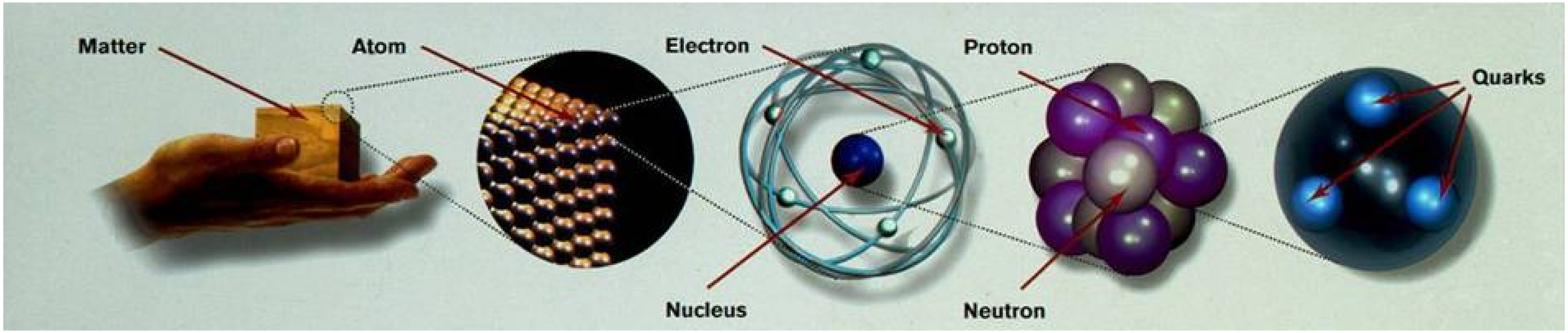
Small objects (smaller than λ) do not disturb the wave
→ small object is not visible
Large objects disturb the wave
→ large object is visible

❖ **all particles have wave properties:**

$$\lambda = \frac{h}{p} = \frac{hc}{\sqrt{E_{kin} \cdot (E_{kin} + 2m_0c^2)}}$$

de Broglie wavelength


Louis de Broglie



10^{-1}m 10^{-9}m 10^{-10}m 10^{-14}m 10^{-15}m

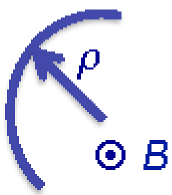
h·c = 1239.84 [MeV fm]

Detection and Identification of Particles

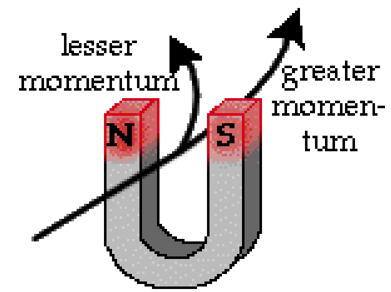
- **Detection** = particle counting (is there a particle?)
- **Identification** = measurement of mass and charge of the particle
  (most elementary particle have $Ze = \pm 1$)

- How:

- charged particles are deflected by B fields such that:

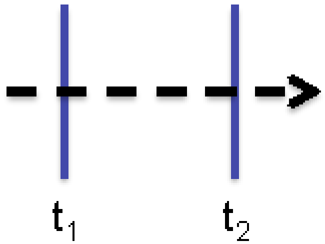


$$\rho = \frac{p}{ZeB} \propto \frac{p}{Z} = \frac{\gamma m_0 \beta c}{Z}$$



$p = $ particle momentum
$m_0 = $ rest mass
$\beta c = $ particle velocity

- particle velocity measured with time-of-flight (ToF) method



$$\beta \propto \frac{1}{\Delta t}$$

- ToF for known distance
- Ionization $-\frac{dE}{dx} = f(\beta)$
- Cherenkov radiation
- Transition radiation

Detection and Identification of Particles

- Detection = particle counting (is there a particle?)
- Identification = measurement of mass and charge of the particle
  (most elementary particle have $Ze = \pm 1$)

- How:

- kinetic energy determined via a calorimetric measurement

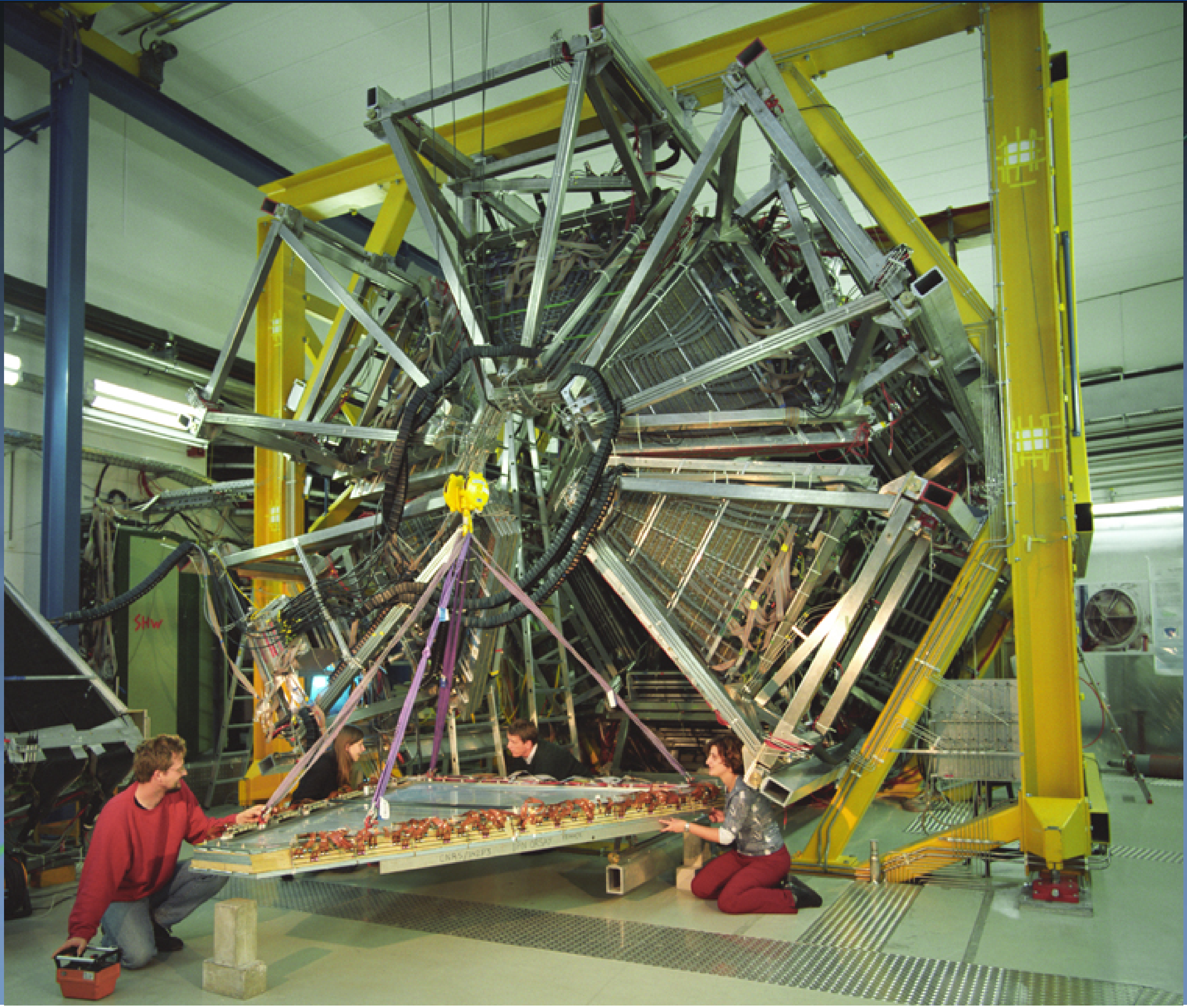
$$E_{kin} = (\gamma - 1) m_0 c^2 \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

- for Z=1 the mass is extracted from E_{kin} and p
- to determine Z (particle charge) a Z-sensitive variable is e.g. the ionization energy loss

$$\frac{dE}{dx} \propto \frac{z^2}{\beta^2} ln(a \cdot \beta^2 \gamma^2)$$

a = material-dependent constant

The HADES experiment @ GSI



Rare ISotope INvestigation at GSI