I. Tools

3. Detectors

Or: How You Measure What You Measure

References: [HG 3,4; PDG 33-35]
(a) What An Experiment Really Is (Ideally)

**Beam Cleanup:** remove charged undesireds by $\vec{B}$

**Collimators:** make sure *all* beam hits target
eliminate “beam halo” (cotravelling undesireds)
#1: define, #2: remove scatters, #3: make sure

**Charged-Beam Dump:** use Cu; after bend to
reduce backscatter; measure beam flux by
Faraday cup; often most radioactive piece during run

**Target:** typ. $1 \text{mol} = 10^{23}$ particles to avoid *rescattering*;
gas @STP: $6 \times 10^{23} \text{dm}^{-3}$; liquid/solid: $6 \times 10^{23} \text{cm}^{-3}$;
often cooled to K or mK (liquid H, $^4$He,…) & polarised

**contaminations:** atomic $e^-$, container walls,
impurities/stabilising compounds (e.g. NaPO$_3$ for P),…

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**If you are a beam, everything looks like a target:**
Nature cannot separate between *signal (good)* and *noise (bad):*
scatter from container, impurities, atomic $e^-$, wrong reaction,
collimators, beam dump; environment: concrete, cosmosics,…

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**Detector:**
collimator often defines angle

**Data Acquisition:**
hardware/software filters, event recording,…

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H. W. Grießhammer, INS, George Washington University
(b) Interaction of Particles With Matter $< 10\text{GeV}$

**Atomic Physics Dominates. Two extremes: real world in-between, mixed.**

**Multiple Scattering** (e.g. electron)
- Usually small $E$ loss, small angle
- Energy & angle spread
- $R_0$: mean range

**Absorption** (e.g. photon)
- "all or nothing"
- $N(x) = N_0 e^{-\mu x}$ with
  $$\mu = \frac{\text{# scatt. centres}}{\text{volume}} \times \sigma \text{ cross section}$$

$\mu$: absorption/attenuation coefficient;

$$X_0 = \frac{1}{\mu} \text{ mean free path}$$

$[\text{HG 3.1}]$  

$[\text{HG 3.3}]$  

$[\text{Knoll 2.4}]$
Photons in Matter

Photoelectric effect (with edges from atomic shells; $\gamma$ absorbed)

$+ \text{ Compton (inelastic) } \gamma Z \rightarrow \gamma e Z' : \text{ multi-scatt. with large energy loss } \implies \text{ quasi-attenuation} \propto Z^{4.5} / E^3$

$+ \text{ Pair Production } \gamma \rightarrow e^+ e^- \text{ in Coulomb of heavy nucleus, coherent} \implies \text{ describe all three by attenuation } \mu = \mu_{\text{photo}} + \mu_{\text{Compton}} + \mu_{\text{pair}}$

\[ Z \times \ln E / E \]

\[ Z^2 \ln E \]
Heavy Charged Particles: \( E \lesssim m \)

Loss mostly by **Coulomb with bound electrons**: avg. ionisation energy \( I \implies \) multiple scattering process

**Material**: the more electrons, the quicker loss

(here normalised to \( \rho_{\text{material}} \))

**Particle**: Rutherford-\( \sigma \) depends only on \( \beta \gamma = \frac{E}{m} \)

at given \( E \): for \( m \rightarrow \), momentum transfer \( \downarrow \)

**Small \( E \) (non-relativistic)**: \( \propto \frac{1}{E} \propto \frac{1}{\beta^2} \)

long passage time \( \implies \) long interaction time

**Minimum at \( \beta \gamma \approx 3 \)**: Hadron Physics problem

above: relativistic rise \( \propto -\ln[1-\beta^2] \)

moving \( \vec{E} \) Lorentz contracted \( \implies \) wider range

eventual saturation (Fermi plateau):

**Specific range**

\[
R = \int_{E_{\text{in,kin}}}^{0} \frac{dE_{\text{kin}}}{dE/dx} \]

**PDG 33.2**

Modelled up to few \% by **Bethe formula** by relativistic QM at

\( 0.1 \lesssim \beta \gamma \lesssim 1000 \) \& \( I \): avg. excitation pot. of material **[derivation: Per]**

\[
- \frac{1}{\rho} \frac{dE}{dx} \approx \frac{4\pi Z_{\text{particle}}^2 \alpha^2}{m_e} \frac{n_e}{\beta^2} \ln \left( \frac{2m_e \beta^2 \gamma^2}{I} \approx 16Z_{\text{mat}}^{0.9} \text{eV} - \beta^2 \right) \quad \text{low} \beta \quad \frac{2 \text{MeV} Z_{\text{part}}^2 \alpha^2}{\text{g/cm}^2 \beta^2} \]

**PDG 33.4**
Electron vs. Heavier Particles at Same Energy/Momentum

- electron: relativistic even for MeV; Fermi plateau at 1 GeV
- proton $E \lesssim 50$ MeV: non-relativistic $\rightarrow$ photoeffect; stopping $\gg$ electron for same $p$: smaller $\beta$
- proton $E \sim 5$ GeV: minimum between Photo/Compton and Bremsstrahlung
- proton $E \gtrsim 10$ GeV: $e^+e^-$ pair production $+$ hadronic reactions, rise to Fermi plateau.

Energy loss at low-$E$: proton $\gg$ electron $\leftrightarrow$ at high-$E$: proton $\ll$ electron $\rightarrow$ Discriminate!
Electrons & Positrons in Matter: Charged but $E \gg m$  

**Atomic Ionisation & Excitation** (like heavy particle)

+ Bremsstrahlung $e^{\pm}Z \rightarrow e^{\pm}Z\gamma$: dominant above $E \approx \frac{600\text{MeV}}{Z}$:

  direction change in Coulomb field of heavy nucleus (Larmor)

  $\Rightarrow$ radiation: $-\frac{dE}{dx} \propto \frac{Z^2 E}{m^2}$: suppressed for all but electrons

+ pair-production from secondary photon $\gg 1\text{MeV}$ $\Rightarrow$ shower

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![Graph](graph.png)

$e^{-}$ energy loss in lead

[PDG 33.11]
Nuclear Reactions

Most important for neutral hadrons at low momenta (neutron, …), any hadron at high momenta:

- eV – keV: fission, capture $\propto 1/\text{velocity}$: time in nucleus

- MeV: elastic/inelastic scattering – most $E$ loss when scattering off light partner

  additional enhancement: $\sigma_{np}(1\text{MeV}) \approx 4\pi a_{np}^2$ with scatt. length $a_{np} \approx 24\text{fm}$

  $\implies$ detect recoil proton & its shower

- $\gtrsim \text{GeV}$: inelastic scattering $\implies$ hadron showers (like in cosmic rays)

  wins over elmag; large range $R_0$: large penetration length

![Graph showing neutron energy vs. cross section (barn)]

[Bethge/Walter/Wiedemann: Kernphysik Fig 5.6]
(c) Detectors

### Common Nuclear Detectors

<table>
<thead>
<tr>
<th>Particle</th>
<th>Detector</th>
<th>Method of Detection</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy charged particles; electrons</td>
<td>Ionization chamber and proportional counter</td>
<td>Total number of ion pairs determined by collecting partners of one sign, e.g. electrons.</td>
<td>Can be used to determine $T_0$ if particle stops in chamber.</td>
</tr>
<tr>
<td>Semiconductor detector</td>
<td>Ionization produces electron-hole pairs. Total charge is collected.</td>
<td>Used to determine $T_0$.</td>
<td></td>
</tr>
<tr>
<td>Geiger counter</td>
<td>Ionization initiates brief discharge.</td>
<td>Good for intensity determination only.</td>
<td></td>
</tr>
<tr>
<td>Cloud chamber or photographic emulsion</td>
<td>Path made visible by ionization causing droplet condensation or developable grains.</td>
<td>Can be used to determine $T_0$ from range. Type of particle can be recognized from droplet or grain count along path.</td>
<td></td>
</tr>
<tr>
<td>Scintillation detector</td>
<td>Uses light produced in excitation of atoms.</td>
<td>$T_0$ proportional to light produced.</td>
<td></td>
</tr>
<tr>
<td>Neutrons</td>
<td>Any of the above using proton recoils from thin organic lining or nuclear reactions with appropriate filling gas</td>
<td>Ionization by recoiling protons.</td>
<td>$T_0$ from end point of recoil distribution.</td>
</tr>
<tr>
<td></td>
<td>Ionization by reaction products.</td>
<td>Some reactions can be used to determine $T_0$.</td>
<td></td>
</tr>
<tr>
<td>Organic scintillator and photomultiplier</td>
<td>Using light produced in excitation of atom by recoiling protons.</td>
<td>$T_0$ from end point of recoil distribution.</td>
<td></td>
</tr>
<tr>
<td>Gamma Rays</td>
<td>Geiger counter</td>
<td>Electrons released in wall of counter ionize gas and initiate discharge.</td>
<td>Good for intensity determination only.</td>
</tr>
<tr>
<td></td>
<td>Nal scintillation detector</td>
<td>Light produced in ionization and excitation by electrons released in the three interaction processes.</td>
<td>$T_e$ proportional to light produced; $h\nu$ inferred from electron energy distributions.</td>
</tr>
<tr>
<td></td>
<td>Semiconductor detector</td>
<td>Electrons produced create electron-hole pairs. Total charge is collected.</td>
<td>$h\nu$ inferred from electron energy distributions.</td>
</tr>
</tbody>
</table>

### Usually needed:
- $\theta_{\text{scatt}} \rightarrow$ position detectors
- particle ID: charge, mass interaction characteristics

$$E = \sqrt{p^2 + m^2}, \quad p = \beta \gamma m$$

### No detector can do all, but most are multifunctional.

$\implies$ Compromise!

Efficiencies always < 100%.

Talk about some popular ones.
ionisation in superheated medium $\Rightarrow$ bubble nucleus $\Rightarrow$ track

charge $Q$; momentum $p[\text{GeV}] \approx 0.3 |Q[e]| \times B[T] \times R[\text{GeV}^{-1}]$; track thickness $\Rightarrow$ particle ID

repetition rate $1 \text{ s}^{-1}$ very slow, but coming back today: CCD cameras, rare processes
Crystal Ball at MAMI (former SLAC & DESY) ≲ GeV; “4π detector”: 93% of solid angle

CMS (LHC@CERN; URL): TeV
Spectrometer: Momentum Selector

$\theta_{\text{scatt}}$ by entrance collimator; $B \approx 1 - 2 \, T$, sophisticated focussing & field mapping, position detector


Fig. 5.4. Experimental set-up for the measurement of electron scattering off protons and nuclei at the electron accelerator MAMI-B (Mainzer Microtron). The maximum energy available is 820 MeV. The figure shows three magnetic spectrometers. They can be used individually to detect elastic scattering or in coincidence for a detailed study of inelastic channels. Spectrometer A is shown in cutaway view. The scattered electrons are analysed according to their momentum by two dipole magnets supplemented by a system of detectors made up of wire chambers and scintillation counters. The diameter of the rotating ring is approximately 12 m. (Courtesy of Arnd P. Liesenfeld (Mainz), who produced this picture) [PRSZR]
Some Position Detectors

Gas Filled Chambers: cheap, large, radiation robust – but fragile $E_{\text{ionisation}} \approx 30 \text{ eV}$

Principle: particle ionises $\Rightarrow$ accelerate electrons (ions) in $E \gtrsim \text{kV/cm}$ field $\Rightarrow$ more ionisation $\Rightarrow$ avalanche accelerated to anode $(1 : 10^4 > 1)$ $\Rightarrow$ detect, resolution $\Delta x \gtrsim 100 \mu\text{m}$

Multiwire Proportional Chamber (MWPC)

Typ. wire-distance $\gtrsim 200 \mu\text{m} \sim \Delta x$ \cite{PRSZA.7} $\Rightarrow$ needs very small structure

Drift Chamber

Measure drift time to anode for 2-dim resolution

Scintillator needed to set trigger for arrival of particle

Typ. wire distance $\sim 2 \text{cm} \gg \Delta x$ \cite{Per11.8}

Needs constant drift velocity (i.e. const. $\vec{E}$-field)

Semiconductor Strips:

$E_{\text{ion}} \approx 3 \text{ eV} \Rightarrow$ shower $\uparrow$, fluctuation $\downarrow$

$\Rightarrow$ great energy resolution

$\Delta x \gtrsim 2 \ldots 5 \mu\text{m}$ (etching) $\Rightarrow$ close to target but prone to radiation damage, expensive
Cu-layer-sandwiched kapton (insulator) foil with micro-holes: strong $\vec{E}$ in hole $\implies$ accelerate, shower

- resolution $\gtrsim 70 \, \mu m$; efficiency $\sim 95\%$
- very stable operation, robust
- large & small structures; “cheap”
More Position Detectors: Scintillators

particle excites/ionises $\Rightarrow$ visible/UV light by de-excitations, augment by PhotoMultiplier Tube PMT

very fast (200 ps), robust, simple

$\Rightarrow$ Workhorses:

– position at spectrometer-end

– trigger/timing:
  set acceptance window for detectors & DAQ

– veto (cosmic,...)

– time-of-flight $\Rightarrow$ $\beta$, but $\frac{\Delta m}{m} \sim \gamma^2 \Delta t$

Materials:

– inorganic crystals (NaI, glass,...)

– organic: plastic, liquid

– semiconductor: very thin

[Per 9.11]
Calorimeters: Scintillators as Shower Detectors

HW Spectrometer: \[ \frac{\Delta p}{p} \sim p : \text{deflection angle} \to 0 \text{ for } p \uparrow \implies \text{measure } E \text{ for } E = \sqrt{p^2 + m^2} \approx p \]

\[ \implies \text{total energy by stopping/destroying particle} \implies \text{length } \propto \ln E = \text{many interaction lengths } R_0, X_0 \]

Poisson: \[ \frac{\Delta E}{E} \propto \frac{1}{\sqrt{E}} ; \text{position & time resolution possible} \]

**Electromagnetic Calorimeter** tuned to \( \gamma, e^\pm \) detection:

Shower \( \propto Z^2 \), small \( X_0 \), narrow (\( \sigma_{\text{Rutherford}} \propto \frac{1}{\sin^4 \theta/2} \))

[Per] discusses a **simple shower model**, but...

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Real World: **GEANT4** Monte Carlo simulation of shower profile/evolution, efficiency!
Electromagnetic Calorimeters: Example NaI Crystals

[Briscoe, Downie, Feldman]

Radiation length $X_0 = 2.6 \text{ cm} \implies 15 \ldots 20 X_0 = 40 - 60 \text{ cm}: \text{ huge mono-crystals}$

Make sure that all shower captured: $\frac{\Delta E}{E} \sim \frac{1 \ldots 2\%}{2 \ldots 4 \sqrt{E} [\text{GeV}]}$ [PRSZR]

672 crystals, $15.7 X_0$ each

**CATS NaI Detector**

1 of 4 largest monocrystals, $24 X_0$, now H1γS

For Compton scattering, meson production, hadron & nuclear spectroscopy, $e^+ e^-$ annihilation, ...
Hadronic Calorimeters

**low-**$E$: short shower, cone wide relative to length but narrow absolutely (bowling ball on bowling ball)

**high-**$E$: long shower, broad but narrowing as $E \uparrow$: Lorentz boost

elemag. loss & strong interactions $\implies$ prefer large $A$ (hard-sphere)

produce other hadrons with large masses $\implies$ less particles

$\lesssim 30\%$ of shower “lost”: $\mu$, $\nu$, $\pi^0$, …

$$\implies \frac{\Delta E}{E} \sim \frac{30\ldots80\%}{\sqrt{E \ [\text{GeV}]}}$$

ID often tricky, ambiguous. $\implies$ Combine with information from TOF, spectrometer, shower profile,…
Particle ID at CB-TAPS

Coincidence plot: Show only events in both PID and NaI

800 MeV photon beam on hydrogen target

PID \equiv Particle ID: thin plastic scintillator \rightarrow particles pass through

Shower discriminant: PID scintillator for “track length”; NaI for calorimetry

neutrals (\gamma, n): lots in NaI, nothing in PID \rightarrow not on this plot

shower profile in NaI: proton signal in 1 crystal only

e^\pm, \pi^\pm 2-6 adjacent crystals (wide shower)
Čerenkov Radiation: Superluminal Shockwave

\[ \beta > \frac{c}{n} \text{ phase velocity of light in medium} \]

\[ \Rightarrow \text{relaxation along path by shock wave} \]

\[ \Rightarrow \text{radiation in cone } \cos \theta_C = \frac{1}{\beta n} \text{ depends only on } \beta \]

**Threshold mode:** only detect light \( \Rightarrow \beta_{\text{min}} \) \((\pi^+ \text{ vs. } K^+ \text{ vs. } p)\)

**Ring Image Čerenkov RICH:** measure \( \theta_C \) \( \Rightarrow \beta \)

tune material, pressure \( \Rightarrow \gamma \sim 1.2 \cdots > 100 \) possible [Per]

AMS@ISS (URL)

“reactor glow”: superluminal \( e^\pm \)

see \( V \) by recoiling light nucleus \( V(X, X)W \)

Super-K, IC\( E \)cube, Antares

\[ \text{Intensity } \propto Z^2 \]

\[ \Theta \propto V \]
More Special Cases

**Short-lived Particles:** by decay products (invariant-mass method); e.g. $\pi^0 \rightarrow \gamma \gamma$

**Neutrons:** next-to-no elmag, only strong:

dote scintillators, use proton conversion in low-$A$ material, $^6\text{Li}(n, \alpha)^3\text{He}$ for $E_n > 20\text{MeV}$, ...

**Muons:** if survives tons of shielding but then shows up in elmag calorimeter, it’s a muon.

**Neutrinos:** missing $E$ and $p$ – or very special detectors.
(d) Some General Detector Characteristics

Resolutions in energy, momentum, spatial, temporal,...

Depend on all variables: particle charge, energy, momentum, hit location, time,...

Measurement uncertainties $\pm \sigma_{E/p/x/t/...}$
usually not Gauß’ian/normal distributed:

Particle number is discrete, minimal detectable energy,...

$\Longrightarrow$ Poisson, Bernoulli, Fano, rare-event statistics,...

But often taken as Gauß’ian to make life easier,
if narrowly peaked: “FWHM concept” $\text{FWHM} = 2.35\sigma_X$
Response dep. on hit charge, $E$, $p$, location in detector, time, . . .

**Sensitivity**: minimum threshold to trigger signal

**Saturation**: maximum possible signal (e.g. before radiation damage)

*wanted* for spatial resolution, *unwanted* for total energy

For spatial resolution:

$$e.g.\text{ energy response function: monoenergetic beam can produce }$$
$$\text{broad spectrum of deposited energies due to subsequent interaction of recoils & secondaries}$$

**Example particle energy**: can often not read off accurately simply from peak position.
Efficiency dep. on hit charge, $E$, $p$, location in detector, time,…

**Detector Efficiency** $0 \leq \varepsilon \leq 1$: probability that particle *actually seen* in detector.

- $\gamma$-ray in gas counter: *few-%*; charge in scintillator: $\sim 100\%$; MeV-neutrinos in huge detector: $10^{-18}$

true event number $= \frac{\text{seen events}}{\text{efficiency} \ \varepsilon \ \pm \ \sigma_{\varepsilon}} = N_{\text{true}} \pm \sigma_{N_{\text{true}}} \implies$ Need calibration!

**Total/Multiparticle Efficiency**: all efficiencies combined.
Time Resolution and Characteristic Times

GW: rare events/high accuracy $\implies$ eliminate coincidentals (cosmic, false starts, ... ) by time-window:

**Trigger:** arrival of particle bunch (pulsed beam), signal in other detector, ...

**Sensitive time:** allowed window after trigger

**Response time:** *form* signal (quick rise!)

**Dead time** from registration to seeing next event; Čerenkov: $10^{-9}$s; Geiger: $10^{-3}$s

Event *pile-up* can extend dead-time.

Correction to true events $N_{true} = \frac{N}{1 - N \tau_D}$

**Recovery time:** until fully sensitive again

Example: $e^-$ form shower $\rightarrow$ propagate (next event unseen) $\rightarrow$ recombine with ions $\rightarrow$ restore equilibrium

**Readout time** e.g. into memory: depends on amount of information, writing speed, ...

**Repetition time:** minimum between events that can be distinguished by *all* components of experiment.

We need repetition time $< \frac{1}{\text{event rate}}$, but not $\ll$.
Next: 4. Quantum Field Theory Recap

Familiarise yourself with: [HH QM-II; Edyn Fields; Ryder 2-4]