Physics 663

Adv Particle Physics

April 2014
Detectors

• Interaction of Charged Particles and Radiation with Matter
  - Ionization loss of charged particles
  - Coulomb scattering
  - Radiation loss by electrons
  - Radiation loss by muons
  - Absorption of $\gamma$-rays in Matter

• Detectors of Single Charged Particles
  - Proportional counters, Spark and streamer chambers, Drift chambers, Scintillation counters, Cerenkov counters, Solid-state counters,
  - Bubble chambers

• Shower Detectors and Calorimeters
  - Electromagnetic-shower detectors
  - Hadron-shower detectors

• References: Donald H. Perkins, Introduction to High Energy Physics, Fourth Edition
Interaction of Charged Particles and Radiation with Matter

• Ionization loss of charged particles
  - charged particles, passing through matter, lose energy primarily through scattering on the electrons in the medium

• Coulomb scattering
  - in scattering off the Coulomb field of the nucleus, the charged particle loses less energy, but suffers a large transverse deflection

• Radiation loss by electrons
  - in addition to losing energy through ionization (above), electrons lose significant energy through radiation
Ionization Loss of Charged Particles

- Charged particles, passing through matter, lose energy primarily through scattering on the electrons in the medium.

- This process results in the Bethe-Bloch formula:

\[
\frac{dE}{dx} = \frac{4\pi N_0 z^2 \alpha^2 Z}{mv^2} A \left\{ \ln \left[ \frac{2mv^2}{I(1 - \beta^2)} \right] - \beta^2 \right\}
\]

- \( I \approx 10 \text{ eV} Z \) (see next page)
- \( dE/dx \)
  - is independent of the mass \( M \) of the particle
  - varies as \( 1/v^2 \) at non-relativistic velocities
  - increase logarithmically beyond minimum at \( E \approx 3Mc^2 \)
  - depends weakly on the medium since \( Z/A \approx 0.5 \) for most media
  - \( \approx 1 - 1.5 \text{ MeV cm}^2 /g \) or \( 0.1 - 0.15 \text{ MeV m}^2 /\text{kg} \)
Excitation energies (divided by $Z$). Those based on measurement are shown by points with error flags; the interpolated values are simply joined. The solid point is for liquid $H_2$; the open point at 19.2 is for $H_2$ gas. Also shown are curves based on two approximate formulae. (from PDG)
Ionization Loss of Charged Particles

• The Bethe-Bloch formula

\[
\frac{dE}{dx} = \frac{4\pi N_0 z^2 \alpha^2}{m v^2} \frac{Z}{A} \left\{ \ln \left[ \frac{2 m v^2}{I(1 - \beta^2)} \right] - \beta^2 \right\}
\]

emerges from Rutherford scattering (moving electron, stationary target atom)

\[
\frac{d\sigma}{dq^2} = \frac{4\pi \alpha^2 z^2}{v^2 q^4}
\]

• For a massive nucleus, there is no energy transfer
• In the rest frame of the electron, the electron acquires a recoil energy \( T \), where \( q^2 = 2mT \)

\[
\frac{d\sigma}{dT} = \frac{2\pi \alpha^2 z^2}{m v^2} \frac{1}{T^2}
\]
Ionization Loss of Charged Particles

- Now, consider the number of such scatters in the energy range \( T \rightarrow T + dT \), in traversing \( dx \), for a medium of atomic number \( Z \)

\[
dN = \frac{2\pi N_0 \alpha^2 Z^2}{m v^2} \frac{Z}{A} \frac{dT}{T^2} dx
\]

- So ionization energy loss is

\[
\frac{dE}{dx} = \int T \frac{dN}{dx} = \frac{2\pi N_0 \alpha^2 Z^2}{m v^2} \frac{Z}{A} \ln \frac{T_{\text{max}}}{T_{\text{min}}}
\]

  - the maximum energy loss is

  \[
  T_{\text{max}} = \frac{2m v^2 E^2}{M^2 + m^2 + 2m E} \approx \frac{2m v^2}{1 - \beta^2}
  \]
  
  - and the minimum is \( I \), the mean ionization potential
Ionization Loss of Charged Particles

\[ \frac{dE}{dx} = \int T \frac{dN}{dx} = \frac{2\pi N_0 \alpha^2 z^2}{mv^2} \frac{Z}{A} \ln \frac{T_{\text{max}}}{T_{\text{min}}} \]

- Insert \( T_{\text{max}} \) and \( T_{\text{min}} \), and add a factor of 2 which accounts for effects such as atomic excitation, and Bethe-Bloch equation is found (after proper relativistic treatment).

\[ \frac{dE}{dx} = \frac{4\pi N_0 z^2 \alpha^2 Z}{mv^2} \frac{2mv^2}{A} \left\{ \ln \left[ \frac{2mv^2}{I(1-\beta^2)} \right] - \beta^2 \right\} \]
Ionization Loss of Charged Particles

- **Relativistic rise**
  - transverse electric field rises with $\gamma$, resulting from more distant collisions
  - polarization effects cut off rise
  - polarization effects are stronger in solids than gas
    - gas: rise $\sim 1.5$
    - solid: rise $\sim 1.1$

![Graph showing ionization loss versus muon momentum for Argon with 5% methane.](image)
Ionization Loss of Charged Particles

- Ion pairs
  - Landau distribution
    - large fluctuations in energy loss
    - higher energy electrons (δ rays)
  - Number of pairs depends on energy required to produce pair in medium
    - helium: 40 eV
    - argon: 26 eV
    - semi-cond: 3 eV

Argon with 5% methane

relativistic rise
Ionization Loss of Charged Particles

- Measured ionization energy loss of electrons, muons, pions, kaons, protons and deuterons in the PEP4/9-TPC
The Bethe-Bloch formula describes the average energy loss of charged particles. The fluctuation of the energy loss around the mean is described by an asymmetric distribution, the Landau distribution. An approximation is

\[ \Omega(\lambda) = \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{1}{2} (\lambda + e^{-\lambda}) \right\} \]

The high energy tail can complicate mass determination.
Bethe-Bloch Equation with Density Corrections

\[- \frac{dE}{dx} = K z^2 Z \frac{1}{A} \beta^2 \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right] \]

\( \mu^+ \) on Cu

Stopping power [MeV·cm²/g]

Muons

Anderson-Ziegler

Lindhard-Scharff

Nuclear losses

\( E_{\mu c} \)

Radiative losses

Without \( \delta \)

Bethe-Bloch

Radiative

\( \beta \gamma \)

[MeV/c]

[GeV/c]

[TeV/c]

\( \frac{1}{100} \)

\( \frac{1}{100} \)

\( \frac{1}{100} \)

PDG
Coulomb scattering

- In scattering off the Coulomb field of the nucleus, the charged particle loses less energy than in scattering from the electrons, since the energy loss formula \( \sim 1/m \)

\[
\frac{dE}{dx} = \frac{4\pi N_0 z^2 \alpha^2 Z}{m v^2} \frac{Z}{A} \left\{ \ln \left[ \frac{2m v^2}{I(1 - \beta^2)} \right] - \beta^2 \right\}
\]

- but suffers a larger transverse deflection in scattering from the nucleus than the electrons

\[
\frac{d\sigma(\theta)}{d\Omega} = \frac{1}{4} \left( \frac{Zz\alpha}{p v} \right)^2 \frac{1}{\sin^4(\theta/2)} \quad \text{incident particle: } z e, p, v \quad \text{target } Ze
\]
Coulomb scattering

• In passing through a layer of material, many scatters occur, resulting in a net angle of multiple scattering which approximates a Gaussian distribution

\[ P(\phi)d\phi = \frac{2\phi}{\langle \phi^2 \rangle} \exp\left(\frac{-\phi^2}{\langle \phi^2 \rangle}\right) d\phi \]

• The rms deflection in distance \( t \) depends on the medium

\[ \phi_{\text{rms}} = \langle \phi^2 \rangle^{1/2} = \frac{ZE_s}{\rho \nu} \sqrt{\frac{t}{X_0}} \]

\[ E_s = \sqrt{4\pi \times 137} \quad mc^2 = 21 \text{ MeV} \]

\[ \frac{1}{X_0} = 4Z^2 \left( \frac{N_0}{A} \right) \alpha^3 \left( \frac{hc}{mc^2} \right)^2 \ln \left( \frac{183}{Z^{1/3}} \right) \]

• \( X_0 \) is called the radiation length
Coulomb scattering

\[ \phi_{\text{rms}} = \langle \phi^2 \rangle^{1/2} = \frac{zE_s}{pu} \sqrt{\frac{t}{X_0}} \quad ; \quad E_s = 21 \text{ MeV} \]

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>( E_c, \text{ MeV} )</th>
<th>( X_0, \text{ g cm}^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen</td>
<td>1</td>
<td>340</td>
<td>63.1</td>
</tr>
<tr>
<td>helium</td>
<td>2</td>
<td>220</td>
<td>94.3</td>
</tr>
<tr>
<td>carbon</td>
<td>6</td>
<td>103</td>
<td>42.7</td>
</tr>
<tr>
<td>aluminium</td>
<td>11</td>
<td>47</td>
<td>24.0</td>
</tr>
<tr>
<td>iron</td>
<td>26</td>
<td>24</td>
<td>13.8</td>
</tr>
<tr>
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<td>82</td>
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<td>6.4</td>
</tr>
</tbody>
</table>

- Measured along one axis (say the x axis), the rms angular deflection is \( 1/\sqrt{2} \) the above expression.
Coulomb scattering

\[ \phi_{\text{rms}} = \langle \phi^2 \rangle^{1/2} = \frac{zE_s}{p\nu} \sqrt{\frac{t}{X_0}} \quad ; \quad E_s = 21 \text{ MeV} \]

- Multiple coulomb scattering limits the precision of determining the direction of a particle.
Coulomb scattering

\[
\phi_{\text{rms}} = \langle \phi^2 \rangle^{1/2} = \frac{zE_s}{pv} \sqrt{\frac{t}{X_0}} \quad ; \quad E_s = 21 \text{ MeV}
\]

• Consider the measurement of the curvature of a particle’s path in a magnetic field
• Radius of curvature of the track (\(\rho\)) is given by expression
  \[p c = B e \rho\]
  \[p(\text{GeV/c}) = 0.3 \text{ B(Tesla)} \rho \text{ (meters)}\]
  - or in terms of deflection in distance \(s\): \(\phi_{\text{mag}} = s/\rho = 0.3 \frac{s}{B / p}\)
• At the same time, the direction of the track is altered by multiple Coulomb scattering

\[
\phi_{\text{scat}} = \frac{0.021}{\sqrt{2}} \frac{1}{p\beta c} \sqrt{\frac{s}{X_0}}
\]

So
\[
\frac{\phi_{\text{scat}}}{\phi_{\text{mag}}} = \frac{0.05}{B \beta \sqrt{X_0 s}}
\]

| Iron, \(X_0 = 0.02 \text{ m}\) |
|---|---|
| \(s\) | \(\phi_{\text{scat}}/\phi_{\text{mag}}\) |
| 1 m | 0.25 |
| 6 m | 0.10 |
Radiation loss by electrons

- In addition to losing energy through ionization (above), electrons lose significant energy through radiation.
- This loss results principally through collisions with the nucleus, and therefore is parametrized by the same length as Coulomb scattering, the radiation length ($X_0$).
- In interacting with the electric field of a nucleus, an electron will radiate photons, in a process known as bremsstrahlung ("braking radiation"):
  - photon energy spectrum $dE'/E'$
  - total loss in distance $dx$
    \[
    \left( \frac{dE}{dx} \right)_{\text{rad}} = -\frac{E}{X_0}
    \]
  - integration easily shows the energy surviving after a thickness $x$
    \[
    \langle E \rangle = E_0 \exp \left( -\frac{x}{X_0} \right)
    \]
Radiation loss by electrons

![Graph showing the radiation loss by electrons in lead (Z = 82)]

- Electrons
- Positrons
- Bremsstrahlung
- Møller ($e^-$)
- Bhabha ($e^+$)
- Positron annihilation

PDG
Radiation loss by electrons

- **Critical Energy** ($E_c$)
  - so the energy loss by electron has two components
    \[
    \frac{dE}{dx} = \left( \frac{dE}{dx} \right)_{\text{ion}} + \left( \frac{dE}{dx} \right)_{\text{rad}}
    \]
  - the ionization loss for high energy electrons is approximately constant
  - however, the energy loss by radiation is proportional to $E$
  - the critical energy ($E_c$) is defined as that energy where these two mechanisms are equal

- for $Z > 5$
  \[ E_c \simeq \frac{600}{Z} \text{ MeV} \]

<table>
<thead>
<tr>
<th>Element</th>
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<th>$E_c$, MeV</th>
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Radiation loss by electrons

\[ \frac{610 \text{ MeV}}{Z + 1.24} \]  
\[ \frac{710 \text{ MeV}}{Z + 0.92} \]
Radiation loss by muons

- For muons with energies above a few hundred GeV, bremsstrahlung and direct $e^+e^-$ production dominate ionization losses especially in heavy materials.
Absorption of $\gamma$-rays in Matter

- $\gamma$-rays are attenuated through three types of processes:
  - Photoelectric effect
    \[ \sigma \sim \frac{1}{E^3} \]
  - Compton scattering
    \[ \sigma \sim \frac{1}{E} \]
  - Pair production
    \[ \sigma \sim \text{constant above threshold} \]

- Above $\sim 10$ MeV, pair production dominant, and attenuation energy independent
Absorption of $\gamma$-rays in Matter

PDG
Absorption of $\gamma$-rays in Matter

- Again, since the process of pair production is closely related to electron beamsstrahlung (interactions with the electron field of the nucleus) both are described by the radiation length

$$I = I_0 \exp \left( -\frac{7x}{9X_0} \right)$$

- Absorption length:

$$9/7 \ X_0$$

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<td>6.4</td>
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Other important processes

• Interactions
  - charged hadrons
    • p, π, K, etc.
  - neutral hadrons
    • neutrons
    • $K^0_L$
  - nuclear breakup

• Decays in flight
  - eg. $\pi \rightarrow \mu \nu_\mu$
## Properties of Materials

| Material | Z  | A  | $(Z/A)$ | Nuclear collision length $\lambda_c$ | Nuclear interaction length $\lambda_I$ | $dE/dx|_{\text{min}}$ | Radiation length $\lambda_r$ | Density $\rho$ | Liquid boiling point at 1 atm(K) | Refractive index $n$ |
|----------|----|----|---------|-------------------------------------|-------------------------------------|-----------------------|-----------------------------|-------------|--------------------------------|---------------------|
| H$_2$ gas | 1  | 1.00794 | 0.99212 | 43.3 | 50.8 | (4.103) | 61.28$^d$ | (731000) | (0.0838)[0.0890] | [139.2] |
| H$_2$ liquid | 1  | 1.00794 | 0.99212 | 43.3 | 50.8 | (4.034) | 61.28$^d$ | 866 | 0.0708 | 20.39 | 1.112 |
| D$_2$   | 1  | 2.0140 | 0.49652 | 45.7 | 54.7 | (2.052) | 122.4 | 724 | 0.169[0.179] | 23.65 | 1.128[138] |
| He      | 2  | 4.002602 | 0.49968 | 49.9 | 65.1 | (1.937) | 94.32 | 756 | 0.1249[0.1786] | 4.224 | 1.024[34.9] |
| Li      | 3  | 6.941 | 0.43221 | 54.6 | 73.4 | 1.639 | 82.76 | 155 | 0.534 | — | — |
| Be      | 4  | 9.012182 | 0.44384 | 55.8 | 75.2 | 1.594 | 65.19 | 35.28 | 1.848 | — | — |
| C       | 6  | 12.011 | 0.49954 | 60.2 | 86.3 | 1.745 | 42.70 | 18.8 | 2.265$^e$ | — | — |
| N$_2$   | 7  | 14.00674 | 0.49976 | 61.4 | 87.8 | (1.825) | 37.99 | 47.1 | 0.8073[1.250] | 77.36 | 1.205[298] |
| O$_2$   | 8  | 15.9994 | 0.50002 | 63.2 | 91.0 | (1.801) | 34.24 | 30.0 | 1.141[1.428] | 90.18 | 1.22[296] |
| F$_2$   | 9  | 18.9984032 | 0.47372 | 65.5 | 95.3 | (1.675) | 32.93 | 21.85 | 1.507[1.696] | 85.24 | —[195] |
| Ne      | 10 | 20.1797 | 0.49555 | 66.1 | 96.6 | (1.724) | 28.94 | 24.0 | 1.204[0.9005] | 27.09 | 1.092[67.1] |
| Al      | 13 | 26.981539 | 0.48181 | 70.6 | 106.4 | 1.615 | 24.01 | 8.9 | 2.70 | — | — |
| Si      | 14 | 28.0855 | 0.49848 | 70.6 | 100.0 | 1.664 | 21.82 | 9.36 | 2.33 | 3.05 | — |
| Ar      | 18 | 39.948 | 0.45059 | 76.4 | 117.2 | (1.519) | 19.55 | 14.0 | 1.396[1.782] | 87.28 | 1.233[283] |
| Ti      | 22 | 47.867 | 0.45948 | 79.9 | 124.9 | 1.476 | 16.17 | 3.56 | 4.54 | — | — |
| Fe      | 26 | 55.845 | 0.45656 | 82.8 | 131.9 | 1.451 | 13.84 | 1.76 | 7.87 | — | — |
| Cu      | 29 | 63.546 | 0.45636 | 85.6 | 134.9 | 1.403 | 12.86 | 1.43 | 8.96 | — | — |
| Ge      | 32 | 72.61 | 0.44071 | 88.3 | 140.5 | 1.371 | 12.25 | 2.30 | 5.323 | — | — |
| Sn      | 50 | 118.710 | 0.42120 | 100.2 | 163 | 1.264 | 8.82 | 1.21 | 7.31 | — | — |
| Xe      | 54 | 131.29 | 0.41310 | 102.8 | 169 | (1.255) | 8.48 | 2.87 | 2.953[5.858] | 165.1 | [701] |
| W       | 74 | 183.84 | 0.40250 | 110.3 | 185 | 1.145 | 6.76 | 0.35 | 19.3 | — | — |
| Pt      | 78 | 195.08 | 0.39894 | 113.3 | 189.7 | 1.129 | 6.54 | 0.305 | 21.45 | — | — |
| Pb      | 82 | 207.2 | 0.39575 | 116.2 | 194 | 1.123 | 6.37 | 0.56 | 11.35 | — | — |
| U       | 92 | 238.0289 | 0.38651 | 117.0 | 199 | 1.082 | 6.00 | $\approx0.32$ | $\approx18.95$ | — | — |

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### Properties of Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
<th>A</th>
<th>$(Z/A)$</th>
<th>Nuclear $a$ collision length $\lambda_T$ [g/cm²]</th>
<th>Nuclear $a$ interaction length $\lambda_I$ [g/cm²]</th>
<th>$\left{\frac{dE/dx}{\text{MeV}}\right}_\text{min}^b$</th>
<th>Radiation length $c$ $X_0$ [g/cm²]</th>
<th>Density [g/cm³]</th>
<th>Liquid boiling point at 1 atm(K)</th>
<th>Refractive index $n$ for gas for gas</th>
<th>Refractive index $n$ for gas for gas</th>
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</thead>
<tbody>
<tr>
<td>Air, (20°C, 1 atm.), [STP]</td>
<td>0.49919</td>
<td>62.0</td>
<td>90.0</td>
<td>(1.815)</td>
<td>36.66</td>
<td>[30420]</td>
<td>(1.205)[1.9391]</td>
<td>78.8</td>
<td>(273) [203]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>0.55009</td>
<td>60.1</td>
<td>83.6</td>
<td>1.991</td>
<td>36.08</td>
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<td>1.00</td>
<td>373.15</td>
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<td>CO₂ gas</td>
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<td>62.4</td>
<td>89.7</td>
<td>(1.819)</td>
<td>36.2</td>
<td>[18310]</td>
<td>(1.977)</td>
<td>410</td>
<td></td>
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<tr>
<td>CO₂ solid (dry ice)</td>
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<td>62.4</td>
<td>89.7</td>
<td>1.787</td>
<td>36.2</td>
<td>23.2</td>
<td>1.563</td>
<td>sublimes</td>
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<tr>
<td>Shielding concrete $f$</td>
<td>0.50274</td>
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<td>99.9</td>
<td>1.711</td>
<td>26.7</td>
<td>10.7</td>
<td>2.5</td>
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<tr>
<td>SiO₂ (fused quartz)</td>
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<td>66.5</td>
<td>97.4</td>
<td>1.699</td>
<td>27.05</td>
<td>12.3</td>
<td>2.20 $^g$</td>
<td>1.458</td>
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<tr>
<td>Dimethyl ether, (CH₃)₂O</td>
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<td>82.9</td>
<td>—</td>
<td>38.89</td>
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<td>46.22</td>
<td>[64850]</td>
<td>(0.4224)[0.717]</td>
<td>111.7</td>
<td>[444]</td>
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<td>75.7</td>
<td>(2.304)</td>
<td>45.47</td>
<td>[34035]</td>
<td>0.509(1.356) $^h$</td>
<td>184.5</td>
<td>(1.038) $^h$</td>
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<td>45.20</td>
<td>—</td>
<td>(1.879)</td>
<td>231.1</td>
<td>—</td>
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<td>(2.239)</td>
<td>45.07</td>
<td>[16930]</td>
<td>[2.67]</td>
<td>261.42</td>
<td>[1900]</td>
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<td>Octane, liquid, CH₃(CH₂)₈CH₃</td>
<td>0.57778</td>
<td>56.7</td>
<td>77.7</td>
<td>2.123</td>
<td>44.86</td>
<td>63.8</td>
<td>0.703</td>
<td>398.8</td>
<td>1.397</td>
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<tr>
<td>Paraffin wax, CH₃(CH₂)n=25CH₃</td>
<td>0.57275</td>
<td>56.9</td>
<td>78.2</td>
<td>2.087</td>
<td>44.71</td>
<td>48.1</td>
<td>0.93</td>
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<tr>
<td>Nylon, type 6 $^i$</td>
<td>0.54790</td>
<td>58.5</td>
<td>81.5</td>
<td>1.974</td>
<td>41.84</td>
<td>36.7</td>
<td>1.14</td>
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<tr>
<td>Polycarbonate (Lexan) $^j$</td>
<td>0.52697</td>
<td>59.5</td>
<td>83.9</td>
<td>1.886</td>
<td>41.46</td>
<td>34.6</td>
<td>1.20</td>
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<tr>
<td>Polytetraphenylene terephthlate (Mylar) $^k$</td>
<td>0.52037</td>
<td>60.2</td>
<td>85.7</td>
<td>1.848</td>
<td>39.95</td>
<td>28.7</td>
<td>1.39</td>
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<tr>
<td>Polyethylene $^l$</td>
<td>0.57034</td>
<td>57.0</td>
<td>78.4</td>
<td>2.076</td>
<td>44.64</td>
<td>—</td>
<td>0.92-0.95</td>
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<tr>
<td>Polyimide film (Kapton) $^m$</td>
<td>0.51264</td>
<td>60.3</td>
<td>85.8</td>
<td>1.820</td>
<td>40.56</td>
<td>28.6</td>
<td>1.42</td>
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<tr>
<td>Lucite, Plexiglas $^n$</td>
<td>0.53937</td>
<td>59.3</td>
<td>83.0</td>
<td>1.929</td>
<td>40.49</td>
<td>≈34.4</td>
<td>1.16-1.20</td>
<td>≈1.49</td>
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<tr>
<td>Polystyrene, scintillator $^o$</td>
<td>0.53768</td>
<td>58.5</td>
<td>81.9</td>
<td>1.936</td>
<td>43.72</td>
<td>42.4</td>
<td>1.032</td>
<td>1.581</td>
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<td>Polytetrafluoroethylene (Teflon) $^p$</td>
<td>0.47992</td>
<td>64.2</td>
<td>93.0</td>
<td>1.671</td>
<td>34.84</td>
<td>15.8</td>
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<tr>
<td>Polyvinyltoluene, scintillator $^q$</td>
<td>0.54155</td>
<td>58.3</td>
<td>81.5</td>
<td>1.956</td>
<td>43.83</td>
<td>42.5</td>
<td>1.032</td>
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<tr>
<td>Aluminum oxide (Al₂O₃)</td>
<td>0.40038</td>
<td>67.0</td>
<td>98.9</td>
<td>1.647</td>
<td>19.27</td>
<td>4.85</td>
<td>3.97</td>
<td>1.761</td>
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<tr>
<td>Barium fluoride (BaF₂)</td>
<td>0.42207</td>
<td>92.0</td>
<td>145</td>
<td>1.303</td>
<td>9.91</td>
<td>2.05</td>
<td>4.89</td>
<td>1.56</td>
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<tr>
<td>Bismuth germanate (BGO) $^r$</td>
<td>0.42065</td>
<td>98.2</td>
<td>157</td>
<td>1.251</td>
<td>7.97</td>
<td>1.12</td>
<td>7.1</td>
<td>2.15</td>
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<tr>
<td>Cesium iodide (CsI)</td>
<td>0.41569</td>
<td>102</td>
<td>167</td>
<td>1.243</td>
<td>8.39</td>
<td>1.85</td>
<td>4.53</td>
<td>1.80</td>
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<tr>
<td>Lithium fluoride (LiF)</td>
<td>0.46262</td>
<td>62.2</td>
<td>88.2</td>
<td>1.614</td>
<td>39.25</td>
<td>14.91</td>
<td>2.632</td>
<td>1.392</td>
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<td>Sodium fluoride (NaF)</td>
<td>0.47632</td>
<td>66.9</td>
<td>98.3</td>
<td>1.69</td>
<td>29.87</td>
<td>11.68</td>
<td>2.558</td>
<td>1.336</td>
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<tr>
<td>Sodium iodide (NaI)</td>
<td>0.42697</td>
<td>94.6</td>
<td>151</td>
<td>1.305</td>
<td>9.49</td>
<td>2.59</td>
<td>3.67</td>
<td>1.775</td>
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<tr>
<td>Silica Aerogel $^g$</td>
<td>0.52019</td>
<td>64</td>
<td>92</td>
<td>1.83</td>
<td>29.83</td>
<td>≈150</td>
<td>0.1-0.3</td>
<td>1.0+0.25ρ</td>
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<tr>
<td>NEMA G10 plate $^t$</td>
<td>0.52019</td>
<td>62.6</td>
<td>90.2</td>
<td>1.87</td>
<td>33.0</td>
<td>19.4</td>
<td>1.7</td>
<td>—</td>
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</table>
## Spatial and Temporal Resolutions

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Accuracy (rms)</th>
<th>Resolution Time</th>
<th>Dead Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble chamber</td>
<td>10 to 150 μm</td>
<td>1 ms</td>
<td>50 ms(^a)</td>
</tr>
<tr>
<td>Streamer chamber</td>
<td>300 μm</td>
<td>2 μs</td>
<td>100 ms</td>
</tr>
<tr>
<td>Proportional chamber</td>
<td>≥ 300 μm(^b,!c)</td>
<td>50 ns</td>
<td>200 ns</td>
</tr>
<tr>
<td>Drift chamber</td>
<td>50 to 300 μm</td>
<td>2 ns(^d)</td>
<td>100 ns</td>
</tr>
<tr>
<td>Scintillator</td>
<td>—</td>
<td>150 ps</td>
<td>10 ns</td>
</tr>
<tr>
<td>Emulsion</td>
<td>1 μm</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Silicon strip</td>
<td>pitch(^e)</td>
<td>(\text{f})</td>
<td>(\text{f})</td>
</tr>
<tr>
<td></td>
<td>3 to 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon pixel</td>
<td>2 μm(^g)</td>
<td>(\text{f})</td>
<td>(\text{f})</td>
</tr>
</tbody>
</table>

---

\(^a\) Multiple pulsing time.

\(^b\) 300 μm is for 1 mm pitch.

\(^c\) Delay line cathode readout can give ±150 μm parallel to anode wire.

\(^d\) For two chambers.

\(^e\) The highest resolution ("7") is obtained for small-pitch detectors (≤ 25 μm) with pulse-height-weighted center finding.

\(^f\) Limited at present by properties of the readout electronics. (Time resolution of ≤ 25 ns is planned for the ATLAS SCT.)

\(^g\) Analog readout of 34 μm pitch, monolithic pixel detectors.
Pictorial Detectors

- **Cloud chamber**
  - condensation on track

- **Emulsions**
  - enhanced silver content, reveals (after development) particle tracks with extreme precision

- **Streamer chambers**
  - ionization of gas generates light through recombination which is photographed

- **Spark chambers**
  - breakdown through electrodes

- **Bubble chambers**
  - liquid is expanded to superheated condition
Cloud Chamber

- Invented by C.T.R. Wilson for study of formation of rain in clouds
- Perfected around 1912
- expands moist air in a closed container
  - expansion cools the air
  - it becomes supersaturated
  - moisture condenses on dust particles
  - ...........or paths ionized by charged particles
- Example: beta particles
Cloud Chamber

A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.
Emulsions

- Photographic film contains tiny crystals (or “grains”) of very slightly soluble silver halide salts such as silver bromide.

- The grains are embedded in gelatine which is melted and applied as a thin coating on a substrate.

- Light or radiation striking a silver halide crystals initiates a series of reactions which produce a small amount of free silver in the grain.

- Free silver produced in the exposed emulsion constitutes the “latent image,” which is later amplified by the development process.

- The free silver grains are easily reduced by “developers” to form relatively large amounts of free silver; the deposit of free silver produces a dark area on the film.

- Emulsions have superb spatial precision (~ 1 µm) but poor time precision, being continuously active.
Emulsions

• Historical example:
  - Discovery of the pion, announced in 1947 by Powell et al.

Four examples of $\pi$-$\mu$-e decays recorded in photographic emulsions.
Emulsions

- Example:
  - Chorus experiment at CERN
  - Searched for tau-neutrino interactions

Proposed sensitivity

Interaction of tau-neutrino ($\nu_\tau$) in emulsion

Decay

Physics 610, detectors
Emulsions

- DONUT (Direct Observation of NU-Tau)
  - Discovered tau neutrino interactions
  - Search for

\[
\nu_\tau + N \rightarrow \tau^- + X
\]
\[
\tau^- \rightarrow (\mu^- \text{ or } e^-) \nu_\mu \nu_\tau \text{ or } \tau^- \rightarrow h^- \nu_\tau
\]
Emulsions

- DONUT

Tau neutrino interaction
Spark Chambers

• Extremely high voltages across gaps lead to breakdown, and emission of light
• Space charge within an avalanche is strong enough to shield external field
  - recombination occurs, and emission of light
• Often multiple gaps were employed
Spark Chambers

![Diagram of Spark Chambers]

- Scintillation Counter
- Photomultiplier Tube
- Base Plate

- 16 modules
Streamer Chambers

• If a short (10 ns) high-voltage pulse (10-50kV/cm) is applied between parallel plate electrodes, a short (2-3 mm) streamer discharge develops

• Good multi-track efficiency and spatial resolution
• triggerable
• long recovery time
• processing of optical images required

• Fermilab experiment, triggered on muons, scanned for $V^0$s
  (search for charm)
Detectors

- Interaction of Charged Particles and Radiation with Matter
  - Ionization loss of charged particles
  - Coulomb scattering
  - Radiation loss by electrons
  - Absorption of $\gamma$-rays in Matter

- Detectors of Single Charged Particles
  - Proportional counters, Spark and streamer chambers, Drift chambers, Scintillation counters, Cerenkov counters, Solid-state counters,
  - Bubble chambers

- Shower Detectors and Calorimeters
  - Electromagnetic-shower detectors
  - Hadron-shower detectors