

Physics of Particle Detection

(Everything from geiger counters to the [ATLAS detector](http://pdg.lbl.gov/atlas): <http://pdg.lbl.gov/atlas>)

Charged particles passing through matter

- lose energy
- scatter

primarily due to

- (a) collisions with atomic electrons
 - dominates energy loss, except for electrons
- (b) scattering from atomic nuclei
 - dominates scattering

These interactions occur frequently

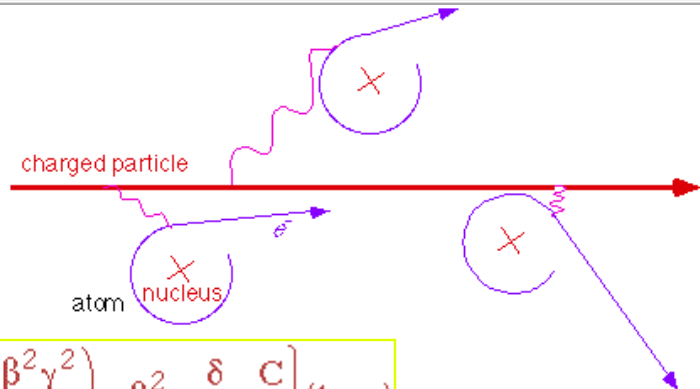
$$\sigma \sim (\text{atomic size})^2 \sim (1\text{\AA})^2 \sim 10^8\text{b} \sim 10^{-20}\text{m}^2$$

Other processes

- (c) bremsstrahlung
 - for electrons and high energy muons ($>0.1\text{TeV}$)
- (d) coherent em radiation
 - Cerenkov radiation (e.m. shock wave) for $v > c/n$
 - Transition radiation ($\gamma \gg 1$) from layered materials
 - Channelling radiation from particles channelled by crystals
- (e) inelastic nuclear reactions
 - for hadrons always, and for all particles at high enough energies

Ionization Energy Loss

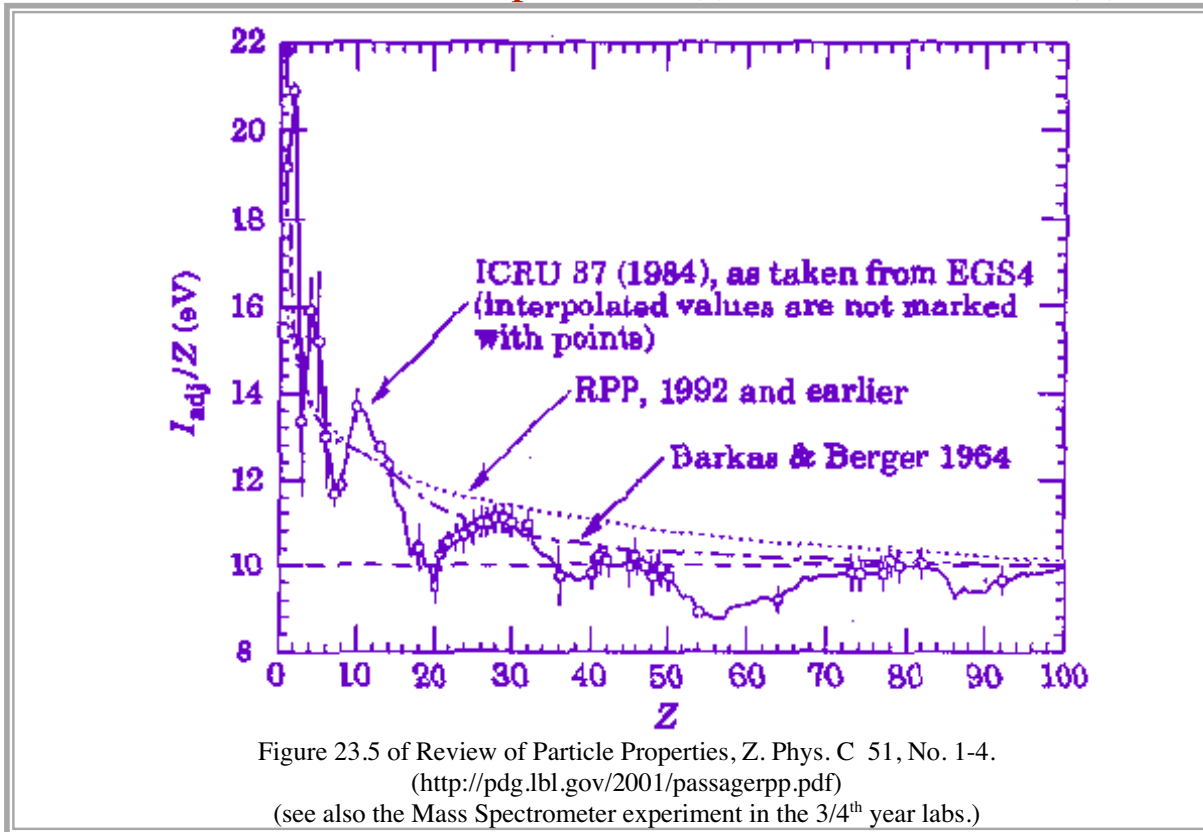
For a heavy ($M \gg m_e$), fast ($\beta \gg \alpha$) charged ($Q = ze$) particle, the ionization energy loss per unit distance travelled in a medium is:



$$\frac{dE}{dx} = \frac{-4\pi n z^2 e^4}{m_e c^2 \beta^2} \left[\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right] (1 + \nu)$$

n	density of electrons in medium
I	effective ionization potential of atoms in medium ($\sim 10\text{ eV}$)
δ	"density effect" due to screening of charged particle's electromagnetic field by polarization of atoms in medium; δ asymptotes to $[2 \ln(\gamma) + \text{constant}]$ for $\gamma \gg 1$
C/Z	"shell corrections" important when $\beta \sim \beta_{\text{atomic electrons}} \sim \alpha$
ν	higher order QED corrections important when $\beta \sim \alpha$

Effective ionization potential (I) / atomic number (Z)

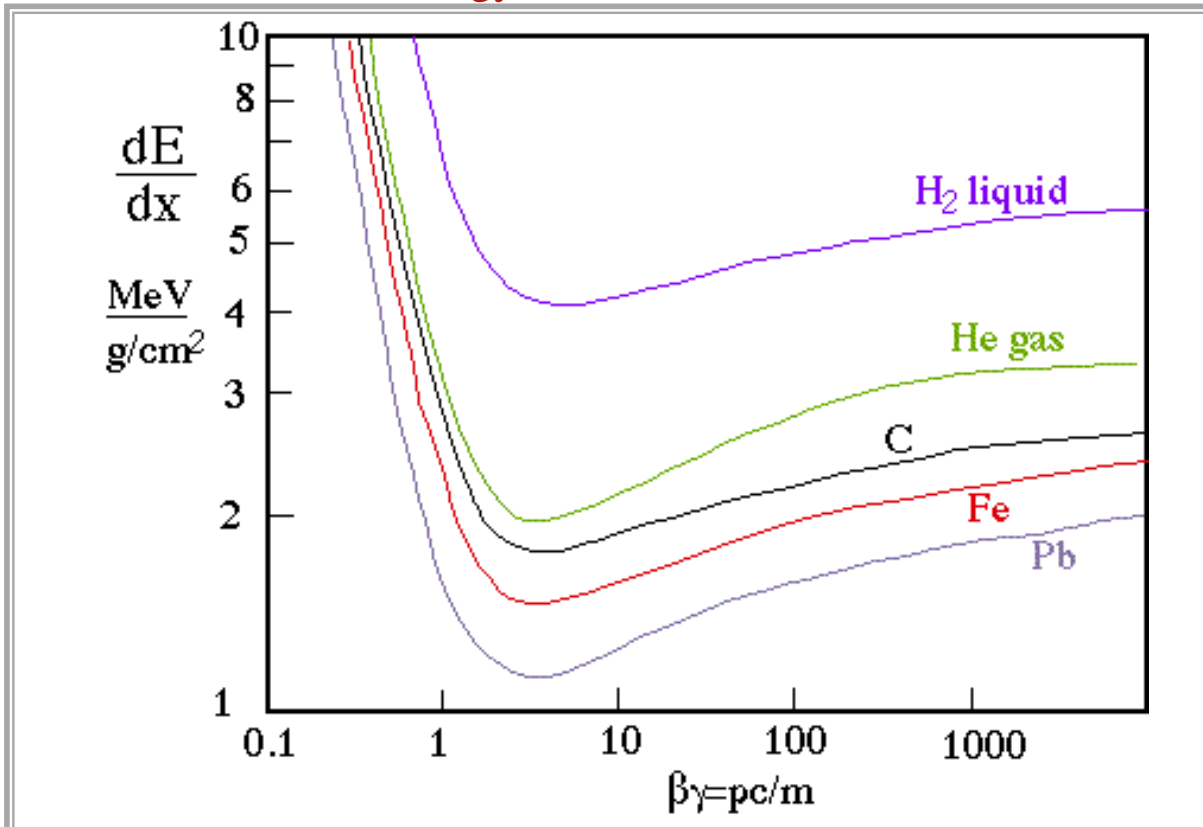


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Ionization energy loss rate in various materials



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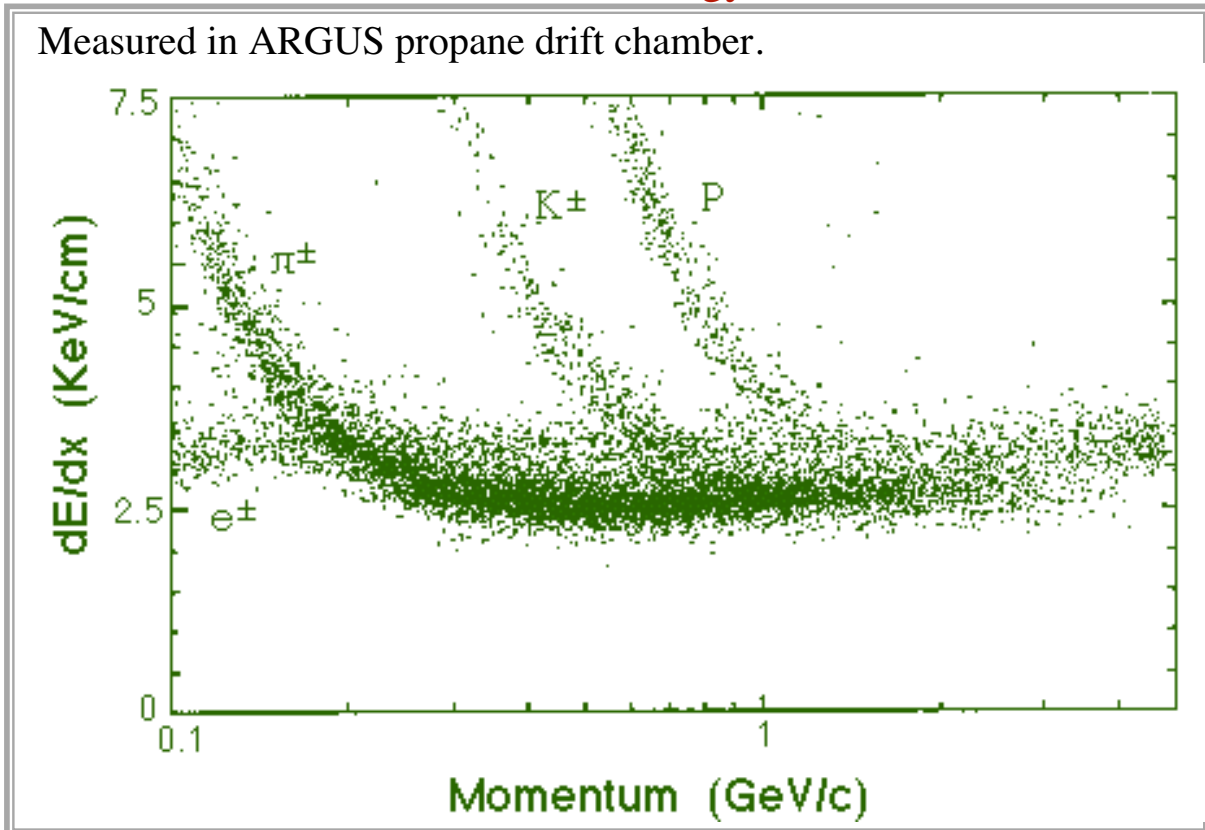
(Gas) Ionization Detectors

The diagram illustrates the operation of a gas ionization detector. It shows an anode (red) and a cathode (purple) separated by a gas (e.g., Ar). An ionizing particle (green arrow) enters from the left, creating ion pairs. The electric field E (indicated by purple arrows) causes electrons to drift towards the anode and positive ions towards the cathode. The drift velocity is given by $u = \mu(E)E$, where μ is the mobility. The ionization rate is approximately $\sim \frac{1 \text{ ion}}{30 \text{ eV}} \frac{dE}{dx}$. The number of ion pairs produced is $\sim \frac{10^2 \text{ ion}}{\text{cm}}$. The signal is produced by the collection of these charges, resulting in a voltage drop of $\sim \frac{10^2 e}{10 \text{ ns}}$ into a 50Ω load, which is equivalent to $1 \mu\text{V}$. A vertical arrow on the right indicates the progression of time.

Liquids and solid ionization detectors have $\sim \times 10^3$ density $\Rightarrow \sim \times 10^3$ dE/dx;
 semiconductors produce one electron-hole pair for about 3eV (Ge) or 4 eV(Si).

Ionization energy loss

Measured in ARGUS propane drift chamber.



Bremsstrahlung

All charged particles scatter from the atomic nuclei and electrons when passing through a medium. When a charged particle is accelerated it radiates, so scattering of charged particles produces radiation. The radiation produced by charge particles passing through a medium is know as "bremsstrahlung".



The mean bremsstrahlung energy loss of a charged particle (mass M , charge ze) is

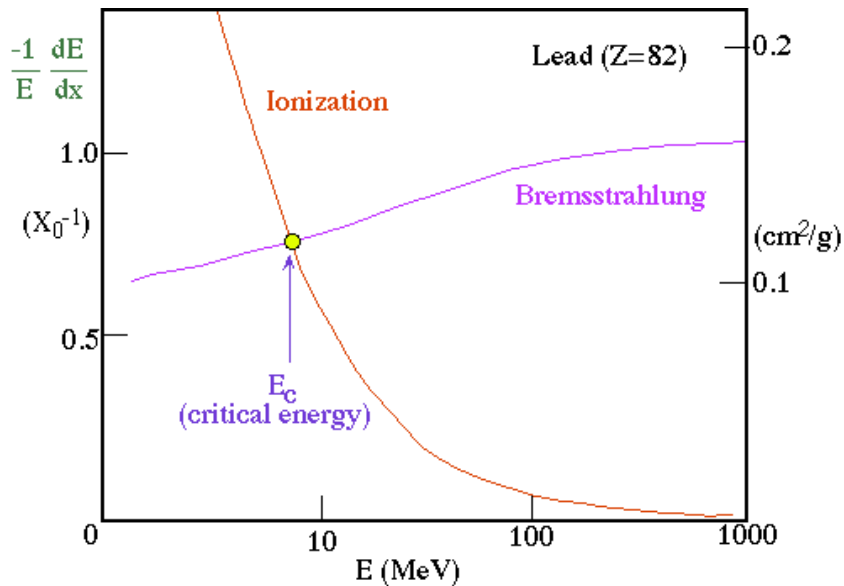
$$dE/dx = -E/X_0$$

where the radiation length, X_0 , for the medium (atom density n_a and atomic number Z) is approximately given by

$$X_0 = M^2/[4n_a e^6 z^4 Z(Z+1) \ln(183/Z^{1/3})]$$

Bremstrahlung dominates the energy loss of electrons above the critical energy, E_c ; ionization dominates at lower energies.

Energy loss of electrons



The critical energy (in lead) of the electron is about 7 MeV; the critical energy of the next lightest particle (the muon) is about half a TeV.