Part 2. Particle Technology : Accelerators and Detectors

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12.1 Accelerators

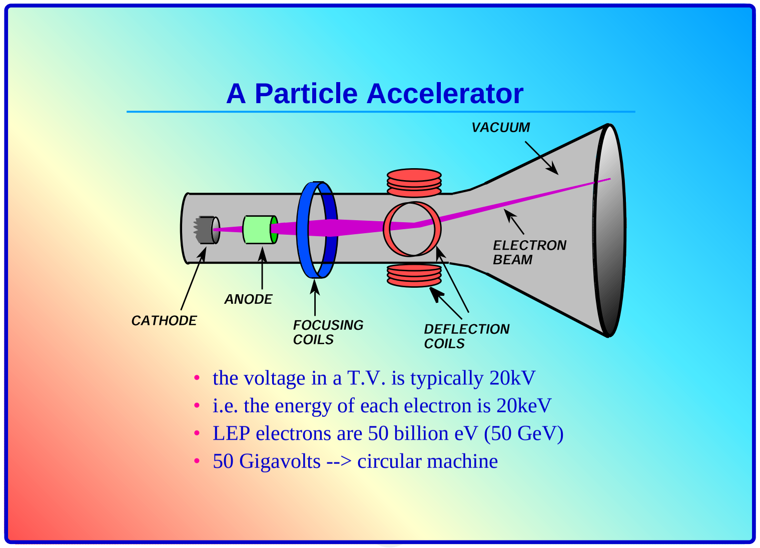

Figure 32: Schematic of a particle accelerator

The machines used for creating fundamental particles are called **Accelerators.** A schematic of a particle accelerator is shown in Figure 32. It is true that the first accelerators were used purely for research reasons, but today, accelerators are used dominantly in the field of medicine. There are hundreds of working accelerators in the United States, only a handful of them used for particle physics research. So, even if you are not thinking about a career in particle physics, the study of acclerators might be relevant for your future!

In order for particles to be accelerated they must be

- Stable

- Charged

This basically means electrons and protons. Pions and Kaons can be accelerated but because their lifetimes are rather short, it limits the purity (because they decay along the way) and the intensity of these beams.

Electron beams are probably the most easy to make and the only *fundamental* particles that can be accelerated. You all know about cathode ray tubes which basically boil off electrons from a cathode and accelerate them. The force used to accelerate particles (i.e. increase their energy) is the electromagnetic force. This means that the particles must be charged in order to be accelerated (i.e. must feel the electromagnetic force). In the simple case of a cathode ray tube, an electric field accelerates electrons to an energy of about 20KeV. If a typical TV tube is about 20cm long, then the fields inside are about 1KV/cm. In order for a singly charged particle to gain 1eV of energy, it must be taken through 1V of potential.

The largest electron linac is 3km long at SLAC (Stanford Linear Accelerator Center) and accelerates electrons and positrons up to 45GeV. They collide to produce Z^0 Gauge Bosons. This means that the electrons achieve energies of about 100GeV/3km, so the field used to accelerate them to this energy must be about 30MV/m.

This energy is impossible to reach with an ordinary DC electric field like that used in a cathode ray tube. **RF Cavities** are used instead. Like a pea on a drum, the RF frequency wave pushes electrons forward at precisely the correct moment as shown schematically in Figure 33. The RF cavities are a few tens of centimeters across and their function is to house a standing wave which changes sign after the electron bunch has passed through, ready to accelerate the next bunch. So, the size of the cavity is intimately related to the frequency of the RF in order for there to be just one (or an interger number of) node(s) across the cavity.

For example,

$$\lambda = \frac{c}{f} \quad (93)$$

$$= \frac{310^8}{310^8} \quad (94)$$

$$= 1m \quad (95)$$

so the size of cavity in this case would be 50cm to set up a wave with a single node.

The particles travel in a vacuum pipe called the **beam pipe**. It is typically about 10cms in diameter and needs to have an extremely high vacuum in order to keep the scattering of the accelerated particles by air molecules to a minimum.

Figure 34 shows a schematic of the time dependence of the voltage in an RF cavity. If the particles are produced uniformly in time, the particles which arrive while the electric field is positive will be accelerated and those arriving while the electric field is negative will be decellerated so the particles will end up in little **bunches** whose size is determined by the characteristics of the RF.

The RF power used is related to the amplitude of the field inside the cavity by:

$$P \propto |E_z|^2 \quad (96)$$

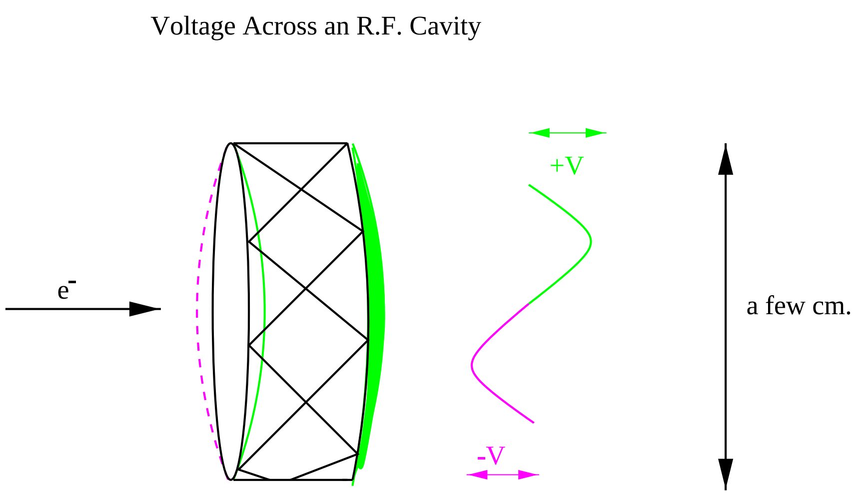

Figure 33: Schematic of an R.F. cavity

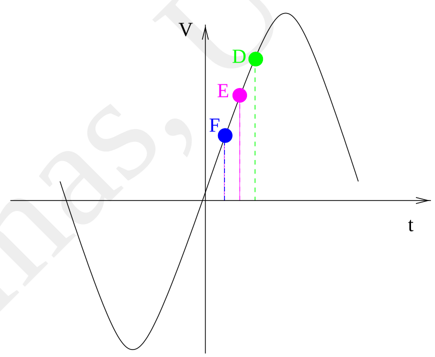

Figure 34: Schematic of an R.F. cavity

12.2 Linear vs Circular Accelerators

The disadvantage of a linear accelerator is that for each increment in energy it is necessary to have yet another cavity. The alternative to this is to use a circular accelerator called a **synchrotron**, where the particles are accelerated with each turn. This means that energy imparted to the particle in each cavity need not be that high as long as the number of repetitions can be made high. Typically, particles go around the ring about 10^5 times before attaining their full energy. In order to accelerate particles in a circular accelerator, they need to be *steered* around the ring and this is done by a series of magnets around the ring. A schematic of a bending magnet is shown in Figure 35 with the field felt by particles passing through it shown.

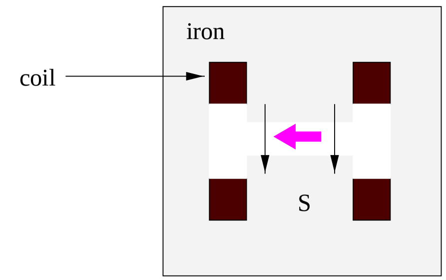

Figure 35: Bending dipole

As the energy of the particles increases, the magnetic field in the bending magnets must be increased as well in order to keep the **radius of curvature** constant. The radius is given by:

$$R = \frac{|p|}{0.3B} \tag{97}$$

In the linear accelerator, the final beam energy depends on the voltage per cavity and the total length, while in the synchrotron, it is determined by the ring radius and the maximum value of B possible in the magnets. The magnets act just like lenses when bending and focussing light. Dipole magnets are used for bending and quadrupole magnets are used for focussing. Figure 36 shows a schematic of a focussing magnet with the field shown.

Quadrupoles focus the particles in one direction and defocus them in the orthogonal direction. Alternate quads have poles reversed and so a system is set up which has a direct analogy with optics. A succession of diverging and converging lenses of equal strength will give a net focussing effect in both directions. Focussing is a characteristic of both linear and circular accelerators. The beam usually fills the cross sectional area of the beam pipe during acceleration, but when the particles have attained their required energy, they will be focussed before they are **extracted** from the accelerator into the experimental region.

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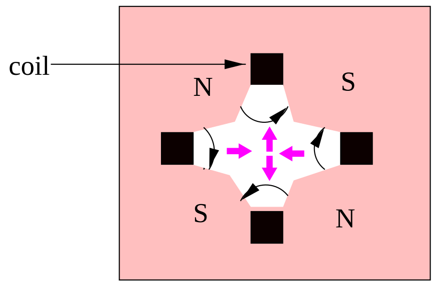

Figure 36: Focussing quadrupole

12.3 Synchrotrons

The particles circulating in a synchrotron do not travel in ideal circular orbits but "wander" in and out of the ideal circular bath in both horizontal and vertical planes. These wanderings are called **betatron oscillations** and they arise from the divergence of the original beam and from small differences in the magnetic bending from ideal and so on.

There are also longitudinal oscillations which are called **synchrotron oscillations** which occur when particles get out of step with the synchronous phase. The synchronous phase is when the increase in momentum per turn from the RF cavities exactly matches the increase in the magnetic fields in the bending magnets. Looking again at Figure 34, the particle arriving in the cavity at point F will recieve a smaller acceleration than the ideal particle (E) and so will be bent into a smaller orbit by the bending magnets. Because it is in a smaller orbit it will arrive earlier the next time around. A particle arriving at point D will recieve a larger acceleration from the RF field and will therefore be bent less than the ideal amount by the bending magnets. This particle will arrive later next time around because the distance it has travelled is slightly longer than the ideal particle.

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13.1 Colliding Beams

High energy physics experiments are performed using these high energy beams by making them collide either with a fixed **target** or by having two beams and making them collide with each other. The former system is called a fixed target machine, the latter is called a colliding-beam machine. The colliding-beam machine has the advantage over the fixed target machine because the center of mass energy available for making new particles is larger for a given beam energy. We proved this in section 5.4.

There is a very special use of the colliding-beam machine which makes the technology of accelerating two beams of particles relatively simple. When the two beams of particles are electron and positron, or proton and antiproton, a synchrotron consisting of a set of magnets and RF cavities adjusted to accelerate the particle in one direction will simultaneously accelerate the antiparticle around the same ring in the opposite direction. This means only one vacuum pipe and one set of magnets. The particles pass through each other as they go around the ring: the beam pipe has a cross-sectional area of 0.1x0.1m^2 $= 0.01m^2$ and the size of a proton is about $10^{-15}x10^{-15}m^2$ so you can calculate the probability that two protons will actually collide during their long journey around the ring. I calculate it to be about 1 chance in a million if you take 10^{13} protons in a bunch which is really the highest beam intensity ever atained. When the particles are extracted therefore, they must be very strongly focussed in order to make them interact! This is done by the series of quadrupole magnets mentioned above.

The performance of the machine is measured by the *Luminsoity*, $\mathcal{L}$ which is given by

$$\mathcal{L} = f\frac{N_1 N_2}{A} \tag{98}$$

where N_1, N_2 are the numbers of particles in the colliding bunches and A is the cross sectional area of the beam.f is the revolution frequency. The interaction rate is given by

$$R = \sigma\mathcal{L} \tag{99}$$

where σ is the cross section for the particular process.

13.2 Synchrotron Radiation

Electron-positron synchrotrons have an important limitation which is absent in a proton machine. Under the circular acceleration, an electron emits **synchrotron radiation,** where the energy emitted per particle per turn is

$$\Delta E = \frac{4\pi}{3}\frac{e^2\beta^2\gamma^4}{R} \tag{100}$$

where R is the radius of curvature of the machine, β is the particle velocity ($\frac{v}{c}$ with c=1) and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$. (Remember to change the units from m^{-1} to GeV) So, considering protons and electrons of the same momentum, the energy loss is proportional to the ratio

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$(\frac{m_e}{m_p})^4$ so it is 10^{13} times smaller for protons than electrons. Thus the radius of curvature must be kept as low as possible for e^+e^-machines which results in long circumference machines. A linear accelerator does not suffer from this problem.

13.3 Advancing the Technology

Although all the principles of operation remain the same, the modern day accelerators which attain the highest energies use superconductivity to improve the performance. This includes lower power dissipation in superconducting cavities, to higher magnetic fields in superconducting magnets for the same power dissipation. There are four very high energy accelerators operating in the world today. The highest energy is being acheived at the Tevatron at FNAL where energies of 1TeV are reached by accelerating and colliding protons.

The highest energy electron-positron machine is LEP (Large Electron Positron) at CERN which is now running at a center of mass energy of 160 GeV. It has a circumference of 27km, which was determined by synchrotron radiation considerations. The physics interaction being studied here is the three Gauge Boson coupling shown in Figure 37. This type of interaction, although well understood within the framework of the Standard Model, has never been studied diretly before. At SLAC, the linear collider accelerates electrons and positrons along the same linac and then they are brought together for collision by way of two large radius arcs. The physics process being studied here is polarized electron positron annihilation to Z^0.

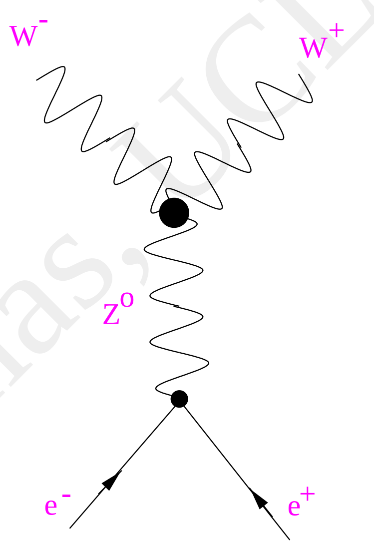

Figure 37: Three Gauge Boson coupling studied at LEP-II

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13.4 Deep Inelastic Scattering

Although this title is rather descriptive, it is not really illuminating. It would better be called "A particle Microscope". Deep Inelastic Scattering (DIS) has been used in the past to probe the inside of the proton. In a similar fashion to using an electron microscope in order to have a short enough wavelength to look at structures which are smaller than the wavelength of visible light, high energy electron (and neutrino) beams have been used to probe very small distances. A beam of point like particles (electrons are the easiest to control and accelerate) impinges on the "target" (the structure to be investigated) which is made of protons and neutrons as all matter is. If the electrons have a high enough energy, they will have a deBroglie wavelength which is smaller than the size of the proton (1fm) and so will scatter off the constituents fo the proton rather than the proton itself. This is illsutrated in Figure 38.

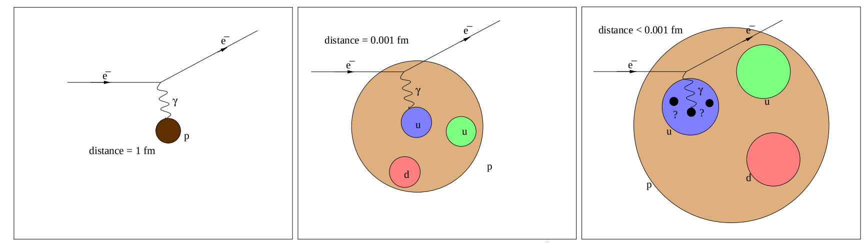

Figure 38: The stages of Deep Inelastic Scattering as energy of the probe increases

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14.1 Detectors

There are three functionally different categories of detectors. The **tracking detectors** measure the position of a particle. The **calorimeters** measure the energy of a particle. The **Cerenkov detectors** measure the velocity of a particle. All detectors rely ultimately on the electromagnetic interaction in order to make a measurement. This reduces the problem to looking at the interactions of

- Charged Particles
- Photons

In the case of detectors which profess to measure some other interaction, such as the strong interaction of hadrons or the weak interaction of neutrinos, what actually happens is that the primary interaction (strong, weak) produces charged particles and photons which are measured in the detector.

The properties of a particle that we are usually interested in measuring are

- Energy, E
- Momentum, **p**
- Charge,Q
- Velocity, v

and all of these quantities can be measured by some combination of measurements by the three aforementioned types of detector. In addition, the mass can be indirectly measured by a combination of the momentum from the tracker in combination with the magnetic field and the velocity measured in the Cerenkov Detector.

14.2 The interaction of charged particles with matter

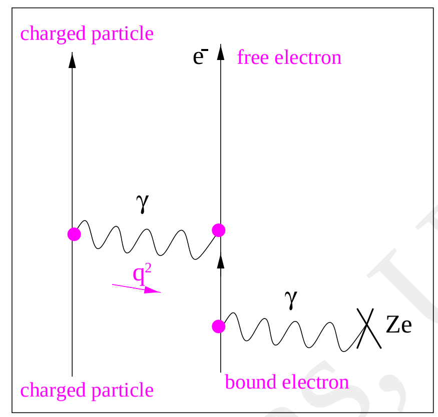
The one thing that these detectors have in common is that they depend on the interaction of the particle with matter: the matter of the detector. There are two processes by which particles lose energy: ionization and Bremstrahlung. The Feynman diagram for ionization energy loss is shown in Figure 39(left). The interaction of a charged particle via the process of ionization or excitation of the constituent atoms in the medium it is traversing and its subsequent energy loss as a function of distance travelled in the medium is described by the Bethe-Bloch formula and depends solely on the charge of the particle in a given medium. This means that the fundmental interaction responsible for charged particle energy loss is the Electromagnetic interaction.

14.3 The Bethe-Bloch Formula

$$\frac{dE}{dx} = \frac{4\pi N_0 z^2 e^4}{mv^2}\frac{Z}{A}\left[ln\left(\frac{2mv^2}{I(1-\beta^2)}\right) - \beta^2\right] \tag{101}$$

where m is the electron mass, z and v are the charge (in units of e) and velocity of the particle, $\beta = v/c, N_0$ is Avogadro's number, Z and A are the atomic number and mass number of the atoms of the medium and x is the parh lenth in the medium meaured in gcm^{-2} or kgm^{-2}. I is an effective ionization potential, averaged over all electrons, with approximate magnitude $I = 10Z$eV. This equation shows that $\frac{dE}{dx}$ is independent of the mass M of the particle, it varies as $1/v^2$ at non-relativistic velocities and after passing through a minimum for $E \approx 3Mc^2$, increases logarithmically with $\gamma = E/Mc^2 = \frac{1}{\sqrt{1-\beta^2}}$.

The dependence of $\frac{dE}{dx}$ on the medium is very weak because $Z/A \approx 0.5$ in all but hydrogen and the heaviest elements. Numerically, $(dE/dx)_{min} \approx 1 - 1.5$ MeV cm^2 g^{-1}. Figure 39(right) shows the energy lost to ionization of a argon-methane gas mixture as a function of $p/Mc = \sqrt{(\gamma^2 - 1)}$. The relativistic rise is associated with the fact that the transverse electric field of the particle is proportional to γ so that more and more distant collisions become important as the energy increases.



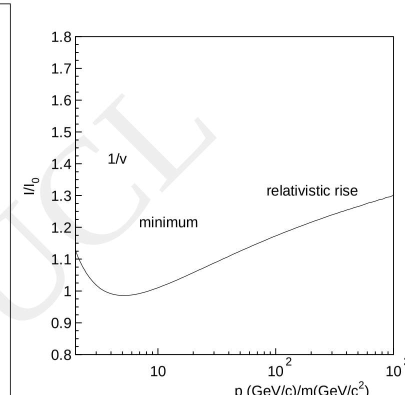


Figure 39: Left:Feynman Diagram for Ionization energy loss for a charged particle. Right: Shape of the Bethebloch energy loss function

14.4 Coulomb Scattering

Although not much energy is lost to the scattering off the nuclei in the ionization loss formula ($\frac{dE}{dx} \propto \frac{1}{m_{nucleus}}$) because of the large mass of the nucleus, transverse *scattering* accompanied by very little energy loss does indeed take place. It is described by the

Rutherford formula for the cross-section as a function of angle θ:

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{1}{4}\left(\frac{Zze^2}{pv}\right)^2 \frac{1}{sin^4(\theta/2)} \tag{102}$$

where the small letters refer to the incident particle and Z is the charge on the nucleus, assumed to act like a point charge. For small scattering angles, the cross section is large, so that in any given layer of material, the net scattering is a result of a large number of small deviations which are independent of one another. The resultant distribution of **multiple scattering** is almost a Gaussian which is very useful when it comes to taking this effect into account in a tracking detector. Gaussian errors are much easier to handle than non-Gaussian ones.

14.5 Bremsstrahlung : braking radiation

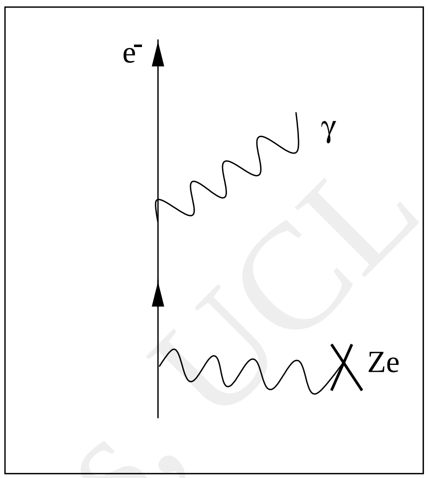


Figure 40: Feynman Diagram for Bremsstrahlung Radiation

Bremstrahlung radiation really only affects electrons because they have such a small mass. Very high energy muons also lose energy this way. The Bremstrahlung Feynman diagram is shown in Figure 40 which shows the electron slowing down in the field of a positively charged nucleus by the attractive EM force between oppositely charged particles. Integrated over the photon spectrum, the total radiation loss of an electron in traversing a thickness dx of medium is

$$(\frac{dE}{dx})_{rad} = -\frac{E}{X_0} \tag{103}$$

where X_0 is intrinsic to the medium and is referred to as the **radiation length.** Therefore, it follows that the average energy of a beam of electrons of initial energy E_0, after traversing a thickness x of medium, will be

$$< E >= E_0 e^{-\frac{x}{X_0}} \tag{104}$$

At high energies, Bremsstrahlung loss for electrons dominates over ionization loss. The radiation length is simply defines as the thickness of the medium which reduces the mean energy of a beam of electrons by a factor e.

At high energies, Bremstrahlung loss dominates. For electrons, the critical energy at which this begins to occur (when ionization loss = Bremsstrahlung loss) is

$$E_c \approx \frac{600}{Z} MeV \tag{105}$$

For muons, this critical energy is in the region of 100GeV

14.6 The interaction of photons with matter

There are three distinct processes by which photons lose energy while traversing a medium. The first is **photoelectric absorption** which is shown in Figure 41(left). The energy loss from this process is proportional to $\frac{1}{E^3}$. The second process is **Compton scattering**, as shown in Figure 41(middle) where by a photon is scattered off the electrons in the atom and loses energy with each collision. The energy loss from this process is proportional to $\frac{1}{E}$. The last process is called **pair-production.** Electron-positron pairs are produced by the photon in the field of a nucleus in order to conserve energy and momentum. The Feynman diagram for this process is shown in 41(right) and this energy loss is approximately constant above about 1GeV.

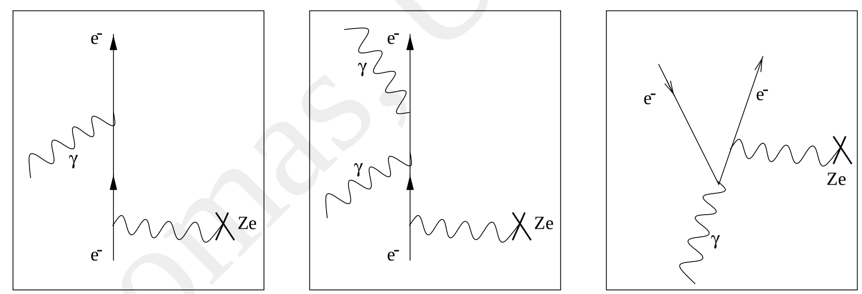


Figure 41: The three processes by which a photon loses energy traversing a medium. From left to right, photoelectric absorption, Compton Scattering and pair-production

The relative contributions from the three processes are shown in Figure 42.

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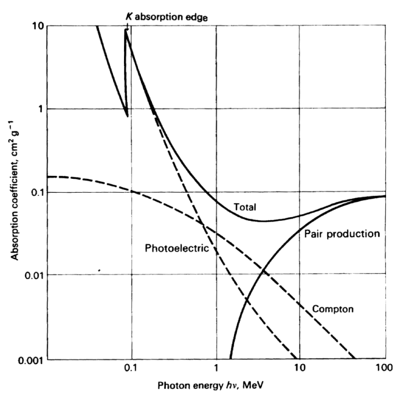

Figure 42: The relative contributions to photon energy loss from the three processes

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