

GAMMA RAYS INTERACTION WITH MATTER

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1. INTRODUCTION

Gamma rays interaction with matter is important from the perspective of shielding against their effect on biological matter. They are considered as ionizing radiation whose scattering by electrons and nuclei leads to the creation of a radiation field containing negative electrons and positive ions.

The main modes of interaction of gamma rays with matter are the photo effect both in its photoelectric and photonuclear forms, Compton scattering and electron positron pair production. To a minor extent, photo-fission, Rayleigh scattering and Thomson scattering also occur.

Each of these processes occurs in different forms. Different types of scattering can occur depending on the quantum-mechanical properties of the gamma photons. Electron positron pairs can be formed in the field of a nucleus and in that of an electron. The photoelectric effect can knock out atomic electrons, whereas the photonuclear reaction would knock out elementary particles from the nucleus.

Gamma rays are emitted in the decay process of radioactive isotopes. On a cosmic scale, Gamma Ray Bursts (GRBs) or Magnetars generate intense gamma radiation fields that could affect space travel and exploration. In addition, bursts of Terrestrial Gamma Ray Flashes (TGFs) occur relatively high in the atmosphere as a result of thunderstorms and are not from the same sources of gamma rays seen on the ground. About 15 to 20 such events are observed per month. Gamma ray bubbles were discovered at the center of the Milky Way Galaxy.

2. GAMMA PHOTONS ENERGY

A particle of zero rest mass such as a neutrino or a gamma photon will have a kinetic energy given by:

$$E = h\nu = \frac{c}{\lambda}, \quad (1)$$

where: h is Planck's constant = 6.62×10^{-27} [erg.sec],
 $\nu = \frac{c}{\lambda}$ is the frequency of the gamma photon,
 $c = 3 \times 10^{10}$ [cm/sec] is the speed of light,
 λ is the wave-length of the electromagnetic radiation [cm].

A result of Relativity Theory is that mass and energy are equivalent and convertible into each other. In particular the complete annihilation of a particle of rest mass m in grams releases an amount of energy E in units of ergs given by the formula:

$$E = mc^2 \text{ [ergs]}$$

Hence we can write a universal energy-mass-radiation equivalence equation as:

$$E = mc^2 = h\nu = \frac{c}{\lambda}$$

This relates mass and electromagnetic radiation through the interesting relationship:

$$m = \frac{h\nu}{c^2} = \frac{1}{\lambda c} \quad (1)'$$

which allows us to suggest here that a clue that the missing black mass and dark energy in the universe could be related to the electromagnetic radiation fields that permeate the known universe. The equation suggests that radiation reaches very high frequencies or very short wave lengths it is equivalent to mass.

The momentum carried by the gamma photon is a vectorial quantity given by:

$$\vec{p}_\gamma = \frac{h\nu}{c} \hat{i} = \frac{E_\gamma}{c} \hat{i} \quad (2)$$

Gamma rays interaction with matter causes the generation of other charged particles such as positrons and electrons at relativistic speeds. If we consider the ratio of the particle speed to the speed of light as:

$$\beta = \frac{v}{c},$$

and its rest mass as m_0 , then the particle's relativistic parameters become:

$$\text{Mass} = m = \frac{m_0}{(1 - \beta^2)^{1/2}} \quad (3)$$

$$\text{Momentum} = p = mv = \frac{m_0 v}{(1 - \beta^2)^{1/2}} = \frac{m_0 \beta c}{(1 - \beta^2)^{1/2}} \quad (4)$$

$$\text{Kinetic energy} = T = m_0 c^2 \left(\frac{1}{(1 - \beta^2)^{1/2}} - 1 \right) = mc^2 - m_0 c^2 \quad (5)$$

$$\text{Total energy} = E = mc^2 = \frac{m_0 c^2}{(1 - \beta^2)^{1/2}} \quad (6)$$

Squaring and rearranging Eqn. 3, we can obtain a relationship between the total energy E and momentum p :

$$\begin{aligned} m^2 &= \frac{m_0^2}{1 - \beta^2} \\ m^2 - \beta^2 m^2 &= m_0^2 \\ m^2 c^2 - v^2 m^2 &= m_0^2 c^2 \\ m^2 c^2 - p^2 &= m_0^2 c^2 \end{aligned}$$

Dividing into $m_0^2 c^2$, we get:

$$\begin{aligned} \left(\frac{p}{m_0 c} \right)^2 &= \left(\frac{mc}{m_0 c} \right)^2 - 1 \\ &= \left(\frac{mc \cdot c}{m_0 c \cdot c} \right)^2 - 1 \\ &= \left(\frac{E}{m_0 c^2} \right)^2 - 1 \end{aligned}$$

Rearranging this equation yields:

$$E^2 = (m_0 c^2)^2 + p^2 c^2 \quad (7)$$

3. PHOTOELECTRIC EFFECT

In the photoelectric process a gamma photon interacts with an orbital electron of an atom. The electron receives kinetic energy from the gamma photon and is knocked out of its orbit. The vacancy created is promptly filled by one of the outer electrons, whose transition is accompanied by the emission of characteristic soft electromagnetic radiation in the x-rays, ultraviolet, or visible regions of the electromagnetic spectrum.

The gamma photon energy is shared among the kinetic energy of the knocked out electron and the characteristic transition radiation according to the conservation of energy equation:

$$E_\gamma = E_e + E_a + E_B, \quad (8)$$

where E_γ is the initial gamma photon kinetic energy,
 E_e is the kinetic energy acquired by the knocked out electron,
 E_a is the kinetic energy of the recoiling atom,
 E_B is the binding energy of the electron in the atom, equal to the excitation

energy of the atom after electron ejection,
for K-shell electrons:

$$E_B = 13.6(Z-1)^2 \text{ eV.}$$

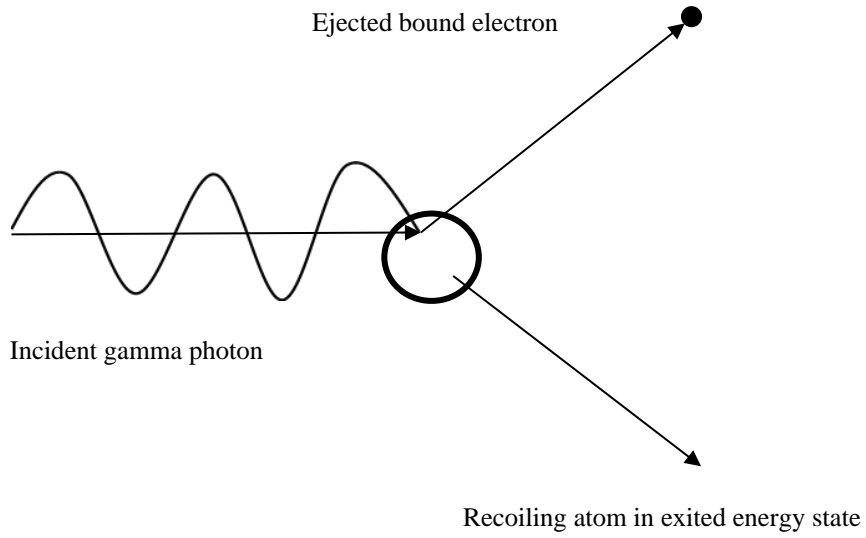


Figure 1. Ejection of a bound electron by a gamma photon: The photoelectric effect.

The recoil atom kinetic energy is of the order of:

$$\left(\frac{m_e}{M} \right) E_e,$$

where M is the mass of the atom,
 m_e is the mass of the electron.

Since:

$$\frac{m_e}{M} \approx 10^{-4},$$

the recoil energy of the atom can be neglected in Eq. 8 leading to:

$$E_e = E_\gamma - E_B = h\nu - E_B, \quad (9)$$

Conservation of momentum also applies:

$$\vec{p}_\gamma = \vec{p}_e + \vec{p}_a \quad (10)$$

For gamma rays energies above 0.5 MeV, photoelectrons are mostly ejected from the K shell of an atom.

The photoelectric interaction cross section is inversely proportional to the gamma photon energy and proportional to the atomic number Z , or the number of electrons in the element it is interacting with. An empirical relation can be written in the form:

$$\sigma_{pe} = \frac{CZ^n}{(h\nu)^m} \approx \frac{CZ^5}{(h\nu)^{3.5}}, \quad (11)$$

where m ranges from 1 to 3, and n ranges from 4 to 5.

This implies that the photoelectric interaction cross section is large for elements of high atomic number Z , and increases with decreasing gamma ray energy as shown in Fig. 2. Gamma ray photons that have been degraded in energy by the process of Compton Scattering subsequently undergo photoelectric absorption.

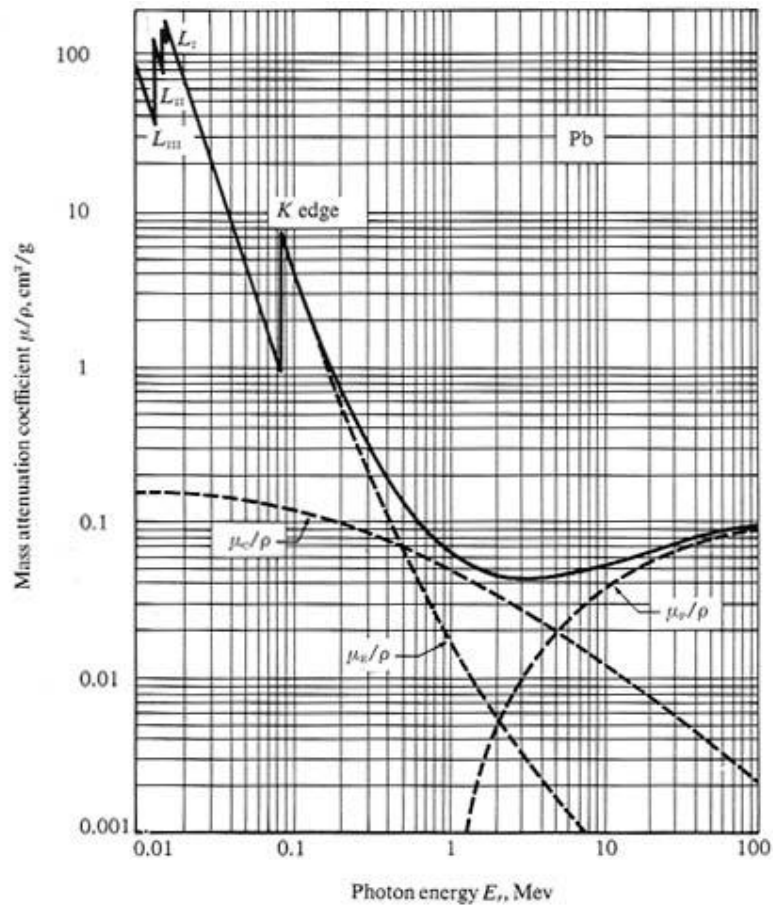


Figure 2. Gamma rays mass attenuation coefficients in lead (Pb), showing the contributions from the photoelectric effect, Compton scattering, and pair production.

The photoelectric process is always accompanied by a secondary emission since the atom cannot remain indefinitely in an excited state, thus:

1. The atom emits x rays and returns to the ground state.
2. Auger electrons are emitted from the outer electronic shells carrying out the excitation energy. This secondary radiation is also later absorbed and occurs in scintillators used in gamma rays detection.

4. PHOTONUCLEAR EFFECT

Nucleons are bound in most nuclei with an energy ranging from 6 to 8 MeV. Thus photons having energies less than 6 MeV cannot induce many nuclear reactions. No radioactive processes except for a few short-lived low-Z nuclides such as ${}^7\text{N}^{16}$, as shown in Table 1 have energies that high.

These energetic gammas exclude access to parts of the turbine hall in Boiling Water Reactors. Since they have a short half-life they are routed through the main steam pipe to the top of the reactor, then to the bottom of the building, before being fed into the turbine. The transit time is sufficient to eliminate much of their radioactivity as ${}^7\text{N}^{16}$ decays into ${}^8\text{O}^{16}$ through negative beta decay with a short 7.1 seconds half-life.

Table 1. Energetic gammas emitting isotopes

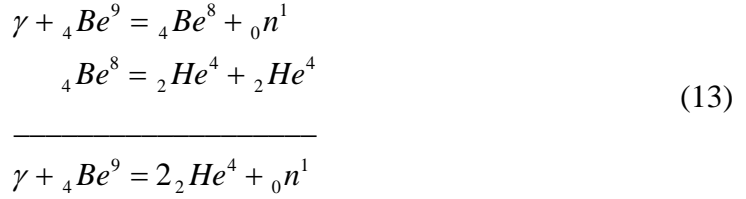
Isotope	Energy (MeV)	Half-life
${}^7\text{N}^{16}$	6.129	7.10 s
	7.115	
${}^{81}\text{Tl}^{208}$	2.6148	3.053 m
	0.5831	
	0.5108	
${}^{11}\text{Na}^{24}$	2.754	15.02 h
	1.369	
${}^{39}\text{Y}^{88}$	1.8361	106.6 d
	0.8980	
${}^{89}\text{Ac}^{228}$	0.9112	6.13 h
	0.9689	
	0.3383	

Reactions produced with such sources are therefore excitations of the nuclei to isomeric levels and the photodisintegration of the deuteron, with a threshold of 2.23 MeV, is such an example:



where the energetic gamma photon is capable of splitting the deuteron nucleus into its constituent proton and neutron.

Another photonuclear reaction is the photo-disintegration of the ${}^9\text{Be}$ isotope with a lower threshold energy of 1.67 MeV:



In this reaction the Be^8 product is unstable and disintegrates within 10^{-14} sec into two helium nuclei.

These reactions can be initiated using electrons of known energy to produce external bremsstrahlung x ray radiation for dissociating the deuteron or beryllium.

Since the lighter elements have large nuclear level spacing, very energetic gamma rays can be emitted, and then used to induce photonuclear reactions. With accelerators operating at a moderate high voltage of 500 to 1,000 keV, high intensities gamma rays at 10^6 photons/sec can be generated, as shown in Table 2.

Table 2. Energetic gamma rays generating reactions.

Reaction	Gamma ray energy (MeV)
${}_1\text{H}^1 + {}_3\text{Li}^7 \rightarrow {}_4\text{Be}^8 + \gamma$	14.8, 15.0, 17.6
${}_1\text{H}^1 + {}_5\text{B}^{11} \rightarrow {}_6\text{C}^{12} + \gamma$	4.0, 11.8, 16.6
${}_1\text{H}^1 + {}_1\text{T}^3 \rightarrow {}_2\text{He}^4 + \gamma$	$19.8 + 0.75E_p^*$

* E_p is the proton's energy.

Photonuclear reactions can be used to produce neutron sources which can be used in a variety of applications such as nuclear medicine and radiography. Table 3 lists such possible sources.

Table 3. Neutron sources based on the photonuclear process.

Source Composition	Reaction	Q value (MeV)	Neutron Energy (MeV)	Neutron yield (per 10^6 disintegrations)
Ra + separate Be	$\gamma + {}_4\text{Be}^9 \rightarrow {}_4\text{Be}^8 + {}_0n^1$ ${}_4\text{Be}^8 \rightarrow {}_2\text{He}^4 + {}_2\text{He}^4$	-1.67	<0.6	0.9
Ra + separate D ₂ O	$\gamma + {}_1\text{D}^2 \rightarrow {}_1\text{H}^1 + {}_0n^1$	-2.23	0.1	0.03
Na ²⁴ + Be	$\gamma + {}_4\text{Be}^9 \rightarrow {}_4\text{Be}^8 + {}_0n^1$ ${}_4\text{Be}^8 \rightarrow {}_2\text{He}^4 + {}_2\text{He}^4$	-1.67	0.8	3.8
Na ²⁴ + D ₂ O	$\gamma + {}_1\text{D}^2 \rightarrow {}_1\text{H}^1 + {}_0n^1$	2.23	0.2	7.8
Y ⁸⁸ + Be	$\gamma + {}_4\text{Be}^9 \rightarrow {}_4\text{Be}^8 + {}_0n^1$ ${}_4\text{Be}^8 \rightarrow {}_2\text{He}^4 + {}_2\text{He}^4$	-1.67	0.16	2.7
Y ⁸⁸ + D ₂ O	$\gamma + {}_1\text{D}^2 \rightarrow {}_1\text{H}^1 + {}_0n^1$	-2.23	0.3	0.08
Sb ¹²⁴ + Be	$\gamma + {}_4\text{Be}^9 \rightarrow {}_4\text{Be}^8 + {}_0n^1$ ${}_4\text{Be}^8 \rightarrow {}_2\text{He}^4 + {}_2\text{He}^4$	-1.67	0.02	5.1

$\text{La}^{140} + \text{Be}$	$\gamma + {}_4\text{Be}^9 \rightarrow {}_4\text{Be}^8 + \text{on}^1$ ${}_4\text{Be}^8 \rightarrow {}_2\text{He}^4 + {}_2\text{He}^4$	-1.67	0.6	0.06
$\text{La}^{140} + \text{D}_2\text{O}$	$\gamma + {}_1\text{D}^2 \rightarrow {}_1\text{H}^1 + \text{on}^1$	-2.23	0.15	0.2
$\text{Ac}^{228} + \text{Be}$	$\gamma + {}_4\text{Be}^9 \rightarrow {}_4\text{Be}^8 + \text{on}^1$ ${}_4\text{Be}^8 \rightarrow {}_2\text{He}^4 + {}_2\text{He}^4$	-1.67	0.8	0.9
$\text{Ac}^{228} + \text{D}_2\text{O}$	$\gamma + {}_1\text{D}^2 \rightarrow {}_1\text{H}^1 + \text{on}^1$	-2.23	0.2	2.6

Energetic gamma photons are emitted from daughter nuclides in the thorium decay chain, such as the 2.6146 MeV of energy gamma ray photon emitted by ${}_{81}\text{Thallium}^{208}$, whose half-life is 3.053 minutes. This energy exceeds the binding energy of the deuteron at 2.23 MeV, and can lead to its disintegration. The presence of thorium and its daughters with deuterium in ordinary or heavy water, would lead to a source of energy from the photonuclear reaction in Eqn. 6. Such an energy release may have been misinterpreted in accounts of cold-fusion occurrence.

Elemental transmutations can also be expected from the presence of neutrons and protons. This suggests that the process of nucleo synthesis may be occurring here on Earth, and not just in the stars. This topic has not been thoroughly investigated, and could also be the source of some observed transmutations in experiments thought to be cold fusion experiments.

The excitation functions for some simple processes such as (γ, n) and (γ, p) reactions and some $(\gamma, 2n)$ and photo fission $(\gamma, \text{fission})$ reactions rise with increasing photon energy, then drop again without an increase in the cross section for competing reactions. The total cross section displays a “giant resonance” behavior. It can be ascribed to the excitation of dipole vibrations of all the neutrons in the nucleus moving collectively against all the protons. The energy of the resonance peak decreases with increasing mass number A. It is 24 MeV for ${}_{8}\text{O}^{16}$, and 14 MeV for ${}_{73}\text{Ta}^{181}$. With gamma rays energy exceeding 150 MeV, such as those generated by cosmic rays, meson production occurs and leads to intra nuclear cascades, spallation and high energy fission.

5. PHOTOFISSION OF NUCLEI

If high-energy protons bombard fluorite or CaF_2 , gamma photons of 6.3 MeV in energy can be produced. These can make the nuclei of uranium and thorium so unstable that they can fission. High energy x rays of 8-16 MeV energy produced by particle accelerators such as the betatron can also cause uranium fission. The threshold energy as shown in Table 4 does not vary much from one nuclide to the other in the thorium and uranium area of mass numbers. However even a 16 MeV photon cannot induce the fission of lead.

Table 4. The photofission threshold energy of some heavy nuclides.

Photofission Threshold [MeV]	Nuclide
5.40	${}_{90}\text{Th}^{230}$
5.18	${}_{92}\text{U}^{233}$
5.31	${}_{92}\text{U}^{235}$
5.08	${}_{92}\text{U}^{238}$
5.31	${}_{94}\text{Pu}^{239}$

6. COMPTON SCATTERING

This is the most dominant process of gamma rays interaction with matter. A gamma ray photon collides with a free electron and elastically scatters from it as shown in Fig. 3. Energy and momentum cannot be conserved if a photon is completely absorbed by a free electron at rest.

Moreover, electrons in matter are neither free nor at rest. However, if the incident photon energy is much larger than the binding energy of the electron, which is its ionization potential in gases or work function in a solid, and if the incident photon momentum is much larger than the momentum of the interacting electron, then we can approximate the state of the electron in a simple model as free and at rest. In this case a gamma ray can interact with a loosely bound electron by being scattered with an appropriate loss in energy.

The total energy of a relativistic particle related to its momentum is from Eqn. 7:

$$E = +[(m_0c^2)^2 + p^2c^2]^{1/2} \quad (14)$$

where we adopted the positive sign after taking the square root.

Denoting the energy of the initial gamma photon as E_γ , and after collision as E_γ' and scattering through an angle θ as shown in Fig. 3, and applying the relativistic conservation of energy and of momentum for such an elastic collision yields:

Conservation of energy:

$$E_\gamma + E_0 = E_\gamma' + (E_0^2 + c^2 p^2)^{1/2} \quad (15)$$

Conservation of momentum:

$$\frac{\bar{E}_\gamma}{c} = \frac{\bar{E}_\gamma'}{c} + \bar{p} \quad (16)$$

where $E_0 = m_0c^2$ is the total energy of the electron when it is at rest = 0.511 MeV, m_0 is the mass of the electron.

The vector equation describing conservation of momentum can be expanded along the incident photon path and perpendicular to it as:

$$\frac{E_\gamma}{c} = \frac{E_\gamma'}{c} \cos\theta + p \cos\varphi \quad (17)$$

$$0 = -\frac{E_\gamma'}{c} \sin\theta + p \sin\varphi \quad (18)$$

Eliminating the angle φ using the relationship:

$$\cos^2 \varphi + \sin^2 \varphi = 1,$$

yields:

$$p^2 c^2 = E_\gamma^2 - 2E_\gamma E'_\gamma \cos \theta + E_\gamma'^2 \quad (19)$$

Substituting the value of $p^2 c^2$ into Eqn. 15, squaring both sides, and canceling the equal terms yields an expression for the outgoing photon energy as:

$$\frac{1}{E'_\gamma} - \frac{1}{E_\gamma} = \frac{1 - \cos \theta}{E_0} \quad (20)$$

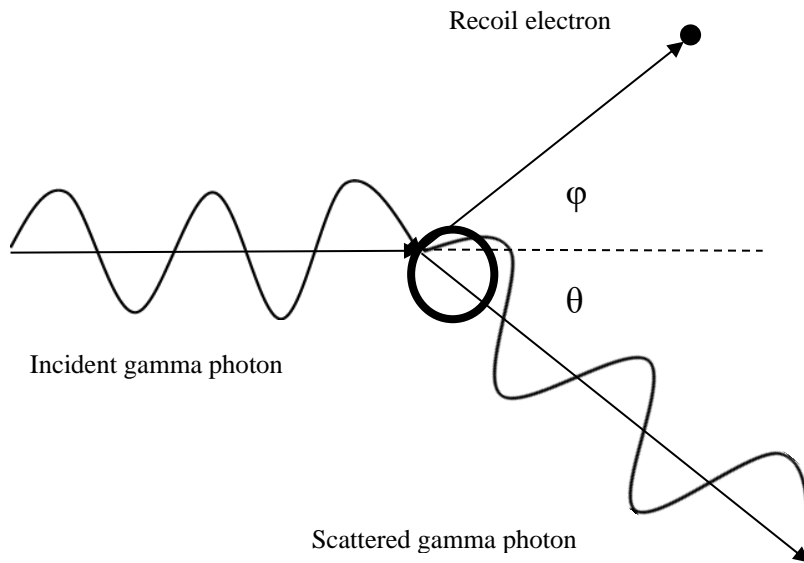


Figure 3. Scattering of a gamma photon by a free electron: Compton scattering.

The last equation can be expressed as the following wave shift relationship:

$$\Delta\lambda = \lambda' - \lambda = \lambda_0 (1 - \cos \theta) \quad (21)$$

where: $\lambda_0 = \frac{h}{m_0 c} = 2.42621 \times 10^{-10}$ [cm], is the Compton wave length of the electron,

m_0 is the electron mass,

λ and λ' is the wave length of the gamma photons before and after scattering,

θ is the scattering angle of the gamma photon.

It is interesting to notice that the wavelength shift is independent of the incident gamma ray energy.

For a given incident photon energy, there exists a minimum energy, corresponding to a maximum wavelength for the scattered gamma photon when it is scattered in the backward direction at $\theta = 180^\circ$. In this case, $\cos \theta = -1$, and:

$$(E'_\gamma)_{\min} = \frac{E_0/2}{1 + E_0/2E_\gamma} \quad (22)$$

For large gamma photons energies the minimum energy of the gamma photon approaches $E_0/2 = 0.25 \text{ MeV}$.

Also, for high energy gamma rays, from Eqn. 20, we get:

$$E'_\gamma \approx \frac{m_0c^2}{1 - \cos \theta} \quad (23)$$

for all scattering angles θ except near 0° .

The probability of the Compton Effect is proportional to the number of electrons in the atom, therefore:

$$\sigma_c \approx \text{const.}Z \quad (24)$$

7. POSITRON ELECTRON PAIR PRODUCTION

A photon of at least 1.02 MeV or the equivalent of two electrons masses ($2m_0c^2$) can create an electron positron pair. In empty space, momentum and energy cannot be conserved. In the vicinity of a nucleus, the process is possible since the nucleus can carry some momentum and energy.

Figure 4 shows the formation of an electron positron pair from an energetic gamma photon in a cloud chamber. A magnetic field perpendicular to the plane of the page curves the particles paths in different directions because of their opposite charges, yet with equal radii because of their equal masses. Some Compton and photoelectric electrons are released when the incoming gamma photon penetrates the chamber wall.

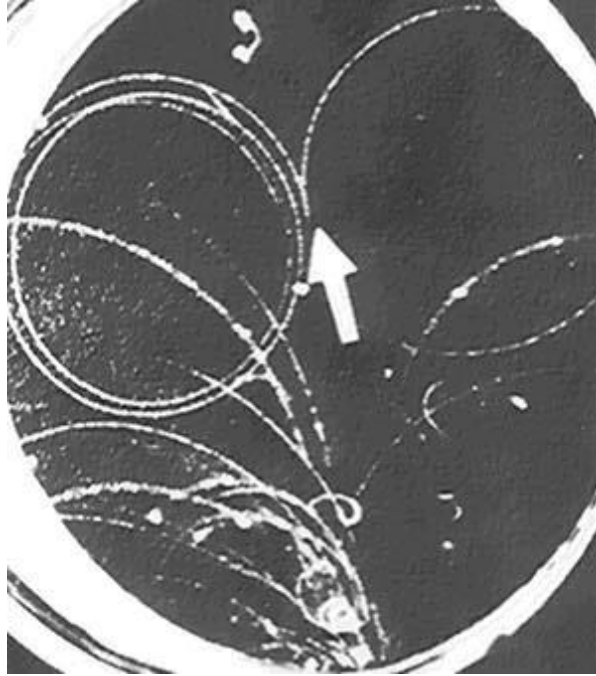


Figure 4. Electron positron pair produced in a cloud chamber, with a magnetic field perpendicular to the page surface, by a high energy gamma photon.

Taking the square root of Eqn. 7 for a relativistic particle yields:

$$E = \pm [(m_0c^2)^2 + p^2c^2]^{1/2} \quad (25)$$

It was argued by Dirac that the ambiguity of the sign in Eqn. 25 is not a mathematical accident. The positive energies E represent a particle of rest mass m_0 and momentum p , and the negative energy states represent a particle of rest mass $-m_0$ and momentum $-p$ as shown in Fig. 5.

No particles can occupy the energy interval:

$$+m_0c^2 \geq E \geq -m_0c^2.$$

Nature is such that all negative energy states are filled with electrons in the absence of any field or matter, and no effect of these electrons is noticeable in the absence of any field or matter. If an electron is ejected from a negative energy state by action of a gamma photon, a hole is formed in the negative energy states like a bubble is formed in a liquid as it is being heated.

The hole in the negative energy states means that the system acquires a mass:

$$-(-m_0) = +m_0,$$

a momentum:

$$-(-\bar{p}) = +\bar{p},$$

and a charge:

$$-(-e) = +e.$$

This bubble or hole corresponds then to a positron of mass $+m_0$, momentum \bar{p} , and charge $+e$.

When the bubble is created an electron also appears in a positive energy state with kinetic energy E_e . Conservation of energy requires that:

$$E_\gamma = h\nu = E_e + E_p + 2 m_0 c^2. \quad (26)$$

This equation can be satisfied in the vicinity of a third particle or a nucleus which can take the excess momentum. If the nucleus does not take much momentum, then the minimum energy for pair production occurs when:

$$E_e + E_p = 0,$$

and consequently, the minimum energy for pair production becomes:

$$(E_\gamma)_{\min} = (h\nu)_{\min} = 2 m_0 c^2 = 2 \times 0.51 = 1.02 \text{ MeV}. \quad (27)$$

The probability of the process or its cross section increases with increasing photon energy and atomic number Z , as shown in Fig. 2. In particular, it is proportional to the square of the atomic number as:

$$\sigma_{pp} \approx \text{const.} Z^2 \quad (28)$$

Pair production is almost always followed by the annihilation of the positron, usually leading to the emission of two 0.51 MeV gamma photons. A single photon is emitted in rare instances where the positron energy is very small, so that a neighboring atom can take the available momentum.

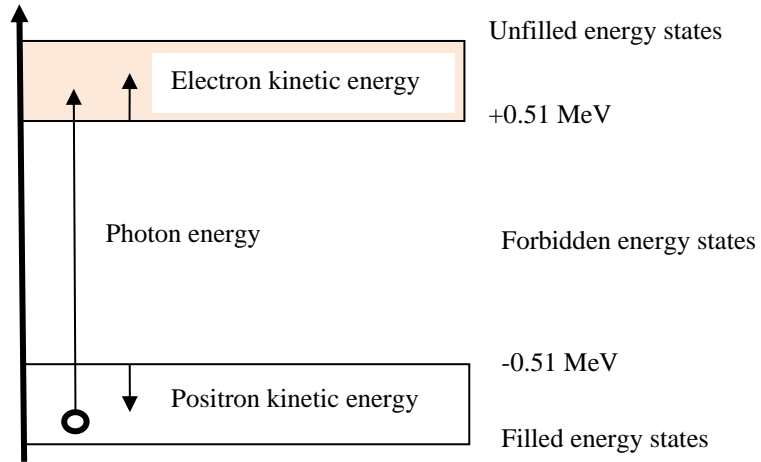


Figure 5. Formation of an electron-positron pair.

A positron and an electron can also form a *positronium*, an atom like structure in which each one of the particles moves about their common center of mass. It is short lived depending on the spin orientation of the particles with 10^{-10} or 10^{-7} sec lifetime, after which they annihilate each other.

8. RAYLEIGH SCATTERING

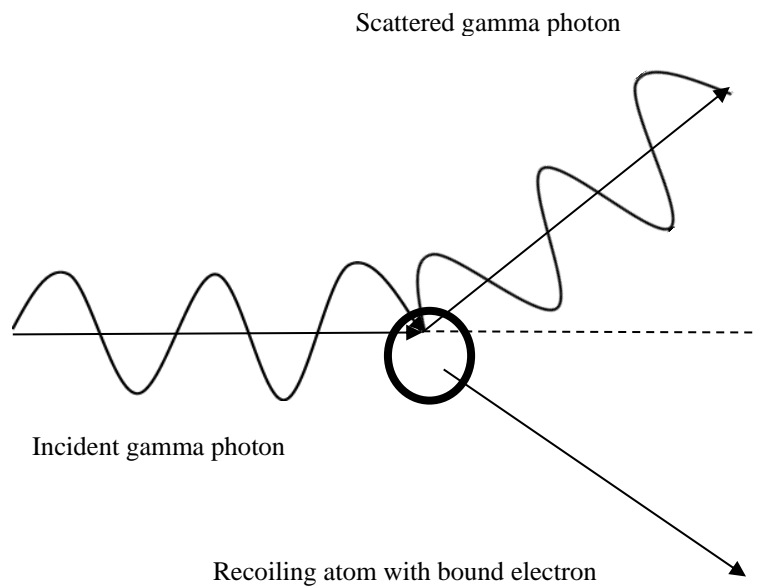


Figure 6. Interaction of a gamma photon with a bound electron: Rayleigh scattering.

If the gamma photon is scattered by a bound electron that is not removed from its atom then Eqns. 8 and 10 still hold. This occurs with the momentum and kinetic energy of the entire recoiling atom replacing that of the electron. Thus in the wave shift Eqn. 21, the mass of the electron must be replaced by the mass of the entire atom. This process shown in Fig. 6 is called Rayleigh scattering, and its wavelength shift is practically negligible.

Rayleigh scattering increases with the atomic number Z of the scattering material, since the binding energy of the inner electrons is proportional to Z^2 implying that an increasing fraction of the atomic electrons is considered as bound. The radiation scattered from all bound electrons in one atom interferes coherently and Rayleigh scattering is peaked around $\theta = 0$.

9. THOMSON SCATTERING

Gamma radiation can scatter on a nucleus with or without excitation of the nucleus. In Thomson scattering, gamma radiation can scatter on the nucleus without excitation. This process interferes coherently with Rayleigh scattering but occurs with a much lower probability.

10. ABSORPTION OF GAMMA RAYS IN MATTER

The atomic cross section for the three main processes: the photoelectric process, Compton scattering, and pair production increase with increasing Z . For this reason, heavy elements are much more effective for gamma radiation than light elements. Lead, aluminum, iron and uranium can be used to shield against gamma rays. Because the photoelectric effect and Compton scattering decrease, and pair production increase with increasing energy, the total absorption in a given element has a minimum, or maximum transparency at some energy. This is also a *window* through which gamma radiation would leak from a given shield as shown in Fig. 2 and Table 5. To close the window, mixtures of different materials are usually used in gamma rays shielding.

The total gamma ray interaction cross section of a substance can be represented as:

$$\sigma_t = \sigma_c + \sigma_{pe} + \sigma_{pp} \quad (29)$$

Table 5. Transparency window for different gamma ray shielding materials

Shielding material	Transparency window [MeV]
Lead	3
Copper	10
Aluminum	22

If we assume that each interaction event leads to the removal of a gamma ray photon from a parallel gamma ray beam, we can represent the attenuation of the beam by a layer of material of thickness x [cm] as follows:

$$I(x) = I_0 e^{-N' \sigma_t x} \quad (30)$$

where the number density N' , or number of atoms or nuclei in 1 cm^3 of material of the material is given by the modified form of Avogadro's law as:

$$N' = \frac{\rho \cdot A_v}{M} \quad (31)$$

where: ρ is the density of the material in $[\text{gm}/\text{cm}^3]$,
 M is the molecular or atomic weight of the material in atomic mass units $[\text{amu}]$.

The attenuation coefficient for gamma rays is defined as:

$$\mu = N' \sigma_t, \quad (32)$$

Consequently Eqn. 30 can be written as:

$$I(x) = I_0 e^{-\mu x} \quad (30)'$$

The physical significance of the attenuation coefficient μ is that it is a summation of the microscopic cross section areas in cm^2 per unit volume (cm^3) of the material. It has units of $(\text{cm}^2/\text{cm}^3)$ or cm^{-1} .

If we define the relaxation length or mean free path giving now units of $[\text{cm}]$ as:

$$\lambda = \frac{1}{\mu}, \quad (33)$$

then a third form of Eqn. 30 can be written as:

$$I(x) = I_0 e^{-\frac{x}{\lambda}} \quad (30)''$$

If we further define the mass attenuation coefficient shown in Fig. 2 for lead as:

$$\mu_m = \frac{\mu}{\rho} \quad (34)$$

which is a measure of the probability of interaction of a gamma photon in a unit mass of a substance, usually taken as 1 gm . Its units are $[\text{cm}^2/\text{gm}]$.

In this case there is still another form of Eqn. 29 that can be written:

$$I(x) = I_0 e^{-\mu_m \rho x} \quad (30)'''$$

Equation 30 in its different forms can be used for the calculation of gamma rays attenuation in matter if the geometry is such that any gamma photon that is scattered at even a small angle leaves the beam, and does not enter the detector. This is designated as the good geometry or narrow beam condition.

11. BUILDUP FACTOR

In practical cases thick shields and non-ideal geometries are used. A gamma photon undergoing Compton scattering can reenter the detector in a broad beam condition. A purely exponential function cannot describe a broad beam condition. The deviation is referred to as the *buildup* of scattered gamma rays that have undergone Compton scattering and are reentering the detector.

Account is practically taken of this effect by the introduction of a *buildup factor* B. The value of B depends on the nature and thickness of the attenuating medium and on the gamma ray energy. The buildup factor is thus defined as:

$$B = \frac{\text{Actual gamma ray flux}}{\text{Flux obtained using exponential attenuation law}}$$

The calculation and choice of build-up factor is a part of the field of gamma ray shielding analysis. In general the practical attenuation law for gamma rays allowing for fluxes takes the form:

$$I(x) = I_0 B(\mu x, E_\gamma) \cdot e^{-\mu(E_\gamma) \cdot x} \quad (30)''''$$

where B is the buildup factor.

12. GAMMA RAYS SHIELD DESIGN

The objective of gamma rays shield design is to find the thickness of a material or a combination of materials that would attenuate the intensity of the radiation to a level that would not adversely affect individuals in the vicinity of the gamma rays radiation field. Mathematically it is an “inverse problem.”

The attenuation factor of a beam of initial intensity I_0 in a shield of thickness x is:

$$\frac{I(x)}{I_0} = B e^{-\mu x}$$

Taking the natural logarithm of both sides we get:

$$\mu x = -\ln\left[\frac{1}{B} \frac{I(x)}{I_0}\right]$$

If the desired attenuation factor and the attenuation factor in the medium used as shield are known, then we can estimate the needed thickness x from:

$$x = -\frac{1}{\mu} \ln\left[\frac{1}{B} \frac{I(x)}{I_0}\right] \quad (35)$$

13. GAMMA RAY BURSTS, GRBs

A massive blast that lasted 200 seconds was detected September 4, 2005 by the Swift satellite. Swift has detected tens of gamma ray bursts since its November 2004 launch. The event occurred about 1.1 billion years after the big bang, the explosion that created the universe an estimated 13.7 billion years ago. The only more distant objects ever detected are a quasar and a single galaxy, both about 12.7 billion light-years away. Gamma ray bursts are brighter than galaxies or even quasars, which are distant, bright objects that scientists theorize are massive black holes that project energy by devouring neighboring stars.

An earlier powerful gamma ray burst occurred on December 27, 2004. The eruption was recorded by NASA's gamma rays Swift observatory and by the National Science Foundation's Very Large Array of radio telescopes, along with other European satellites and telescopes in Australia. The Swift satellite observatory, named Swift for its speedy pivoting and pointing was among the instruments that detected the flare. It was launched to probe the workings of black holes. The satellite, operated by the Goddard Space Flight Center in Greenbelt, is designed to detect gamma ray outbursts and quickly pivot to record them. It also recorded the afterglow of the blast.

The gamma rays hit the Earth's ionosphere and created ionization, briefly expanding it. The flash of gamma rays was so powerful that it bounced off the moon and lit up the Earth's upper atmosphere. Had this happened within 10 light years away from the Earth, it would have severely damaged its atmosphere and possibly triggered a mass extinction. It would have destroyed the ozone layer causing abrupt climate change and mass extinctions due to increased space radiation reaching the Earth's surface. One could wonder whether major species die offs in the past might have been triggered by closer such stellar explosions.

The gamma ray burst occurred at a neutron star called SGR 1806-20 about 50,000 light years away from the solar system. A light-year is the distance light travels in a year, about 6 trillion miles or 10 trillion kilometers. The blast was 100 times more powerful than any other similar witnessed eruption.

Gamma ray bursts are thought to occur when a star runs out of hydrogen fuel and starts to burn heavier elements produced by nuclear fusion in the nucleo-synthesis process. Eventually the star is left with only iron, which will not burn. The star collapses and, if it is large enough, creates a black hole with gravity so intense that nothing can escape from it. The event is accompanied by a spectacular gamma ray explosion.

A neutron star is the remnant of a star that was once several times more massive than the sun. When their nuclear fuel is depleted, they gravitationally collapse as a supernova. The remaining dense core is slightly more massive than the sun but has a diameter typically no more than 12 miles or 20 kilometers. Millions of neutron stars fill the Milky Way galaxy. A dozen or so are ultra-magnetic neutron stars or magnetars. The magnetic field around one is about 1,000 trillion gauss, strong enough to strip information from a credit card at a distance halfway to the moon.

Of the known magnetars, four are called Soft Gamma Repeaters, or SGRs, because they flare up randomly and release gamma rays. The flare on SGR 1806-20 unleashed about 10,000 trillion trillion trillion or 10^{36} watts of energy.

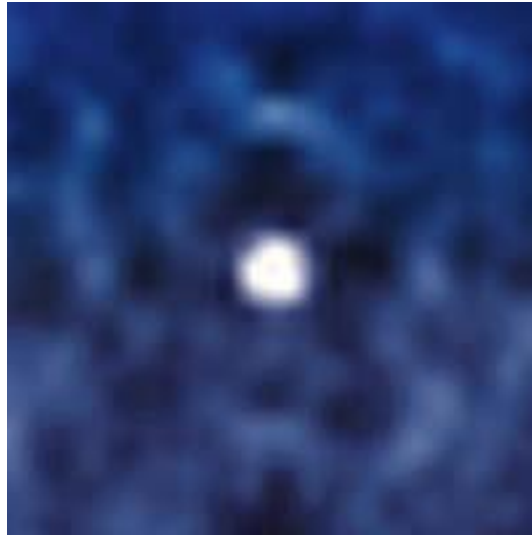


Figure 7. Gamma ray burst. The aftermath of the blast is a smoldering oblong ring that glows for several days after the flare, or afterglow, caused by debris launched into the gas surrounding the star.

The flare was observed in the constellation Sagittarius or the Archer. The explosion, which lasted over a one tenth of a second, released energy more than the sun emits in 150,000 years.

This might have been an once-in-a-lifetime event for astronomers, as well as for the neutron star. Only two other giant flares were observed within 35 years, and this event was one hundred times more powerful than any of them.

SGR 1806-20 was one of only about a dozen known magnetars. These fast spinning, compact stellar corpses, no larger than a big city, create intense magnetic fields that trigger explosions.

The naked eye and optical telescopes could not spot the explosion because it was brightest in the gamma ray energy range. No known eruption beyond our solar system has ever appeared as bright upon arrival. The event equaled the brightness of the full moon's reflected visible light.

The SGR 1806-20 star spins once on its axis every 7.5 seconds, and it is surrounded by a magnetic field more powerful than any other object in the universe which may have snapped in a process called magnetic reconnection. Other scientists believe the magnetic field of the magnetars can shift like an earthquake, causing it to eject a huge burst of energy.

14. OCCURRENCE OF GAMMA RAY BURSTS

Every day gamma ray bursts illuminate the sky. They come from random directions from the universe and have become the target of intense research and study by astronomers and cosmologists.

In 1991 NASA launched the Compton Gamma Ray Observatory carrying an instrument called the Burst and Transient Source Experiment, BATSE designed specifically for the study of the enigmatic GRBs and has led to a new understanding of their origin and distribution in the universe.

Lasting anywhere from a few milliseconds to several minutes, GRBs shine hundreds of times brighter than a typical supernova and about a million trillion times as bright as the sun, making them briefly the brightest source of cosmic gamma-ray photons in the observable universe. GRBs are detected about once per day from random directions of the sky.

GRBs were for a while the biggest mystery in high energy astronomy. They were discovered serendipitously in the late 1960s by USA military satellites which were on the lookout for potential Russian nuclear testing in violation of the atmospheric nuclear test ban treaty. These satellites carried gamma ray detectors since a nuclear explosion produces gamma rays. Prompt gamma rays are emitted from the fission process, followed by delayed gamma rays from the resulting fission products.

As recently as the early 1990s, astronomers did not even know if GRBs originated at the edge of our solar system, in our Milky Way Galaxy or far away near the edge of the observable universe. A slew of satellite observations, followup ground-based observations, and theoretical work have allowed astronomers to link GRBs to supernovae in distant galaxies.

From the large energy, the rapid variability and the energy spectrum of the radiation it is expected that one or more compact objects such as black holes, or neutron stars must be involved. The gamma radiation itself originates from the outflowing material which expands at more than 99.995 percent of the speed of light.

15. CUSPED FIELD MODEL OF GRBs

A model for GRBs must address two critical questions:

1. The process by which matter is extremely accelerated. Substantial energy must be distributed into a small mass to make the large velocities possible.
2. The process of radiation generation. Accelerated matter does not radiate by itself. An additional process must generate the high energy emission.

We propose that gamma ray bursts could evolve as a result of the occurrence within the magnetars of a cusped magnetic field configuration.

In most systems in which a plasma is confined by a magnetic field that surrounds it smoothly without a discontinuity, there is a tendency toward the creation of instabilities. This is so because the magnetic lines of force which are stretched around the plasma can shorten themselves by burrowing into the gas and thus force it outward.

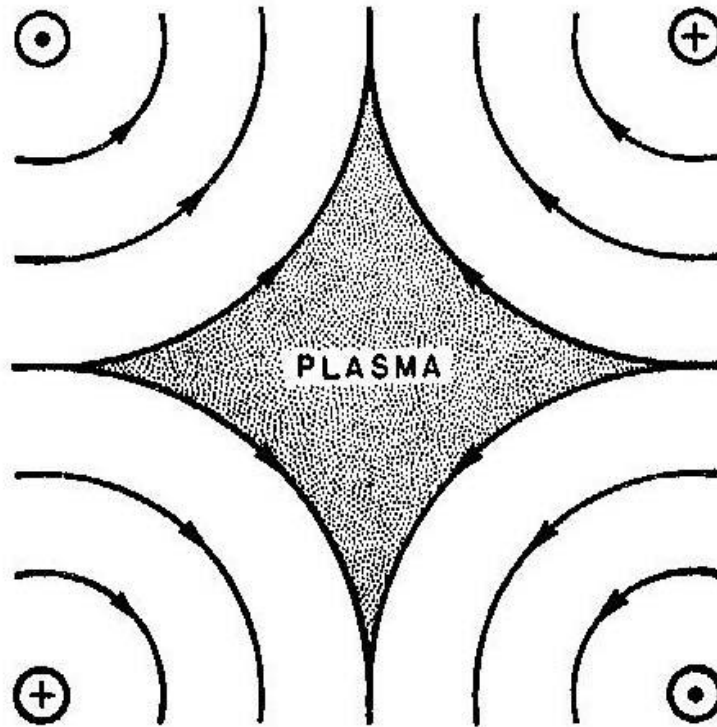


Figure 8. Cusped magnetic field configuration produced by an array of four line currents alternating in direction.

A confinement system which is absolutely stable against arbitrary deformations, even of finite amplitude, of the plasma can be obtained if the magnetic field lines curve away everywhere from a diamagnetic plasma. This means that the magnetic field and plasma interface is everywhere convex on the side toward the plasma. To satisfy this curvature requirement, the magnetic field must possess cusps, which are points or lines, or both, through which the magnetic field lines pass radially outward from the center of the confinement region as shown in Fig. 8.

A laboratory geometry of this kind is called a picket fence, and consists of two layers of parallel wires carrying currents in alternating directions so that the magnetic field has a series of cusps. The magnetic fields are generated in the vicinity of the walls decreasing the power needed in maintaining them. This advantage is superseded by the more important advantage of stable confinement.

Another type of cusped geometry is the biconal cusp produced by a pair of magnetic field circular coils with the currents in them flowing in opposite directions. A succession of cusped configurations can generate a toroidal cusped system.

If there is a loss of plasma from the central volume, the lines of force would have to stretch to fill the volume previously occupied by the plasma. Since this requires extra energy expenditure, this type of instability would not probably occur.

In the cusped configuration a singular condition exists at the center where the magnetic field goes exactly to zero. A particle passing through this point will experience a large field change occurring in a time interval less than the gyromagnetic period, particularly as this period

is lengthened by the decrease in the magnetic field strength. The magnetic moment becomes no longer an adiabatic invariant of the system.

In the special case of a particle actually passing through the point where the magnetic field is zero, the particle will momentarily travel in a straight line and its motion will bear no relationship to that before its passage through this point. The magnetic energy of the particle can theoretically reach an *infinite* value along the zero magnetic field line.

If one considers a confined plasma rather than a particle, one must consider the problem of Magneto Hydro Dynamic (MHD) cumulation of energy near a zero field line.

Let us consider a perfectly conducting and incompressible cylindrical plasma to be immersed in a quadrupolar steady external magnetic field:

$$\bar{B}_e = B_0 \nabla \bar{x} \bar{y}. \quad (36)$$

In the absence of currents and velocities the plasma is under an unstable equilibrium to a linear velocity perturbation:

$$\begin{aligned} v_x &= U\bar{x}, \\ v_y &= U\bar{y}. \end{aligned} \quad (37)$$

The MHD equations of motion which do not depend on the z axis variable can be exactly solved with the velocity perturbation as an initial condition.

The motion generates an axial current j_z in the z direction. Due to the pinch effect or the Lorentz force:

$$\bar{F} = \bar{j} \times \bar{B}, \quad (38)$$

the circular section of the cylinder is deformed into ellipses of axes (0x, 0y). After a time comparable to the ratio of the initial cylinder radius to the Alfvén velocity:

$$V_A = \frac{B_0}{(4\pi \rho)^{1/2}} \quad (39)$$

a cumulation process occurs and the elliptical cross section is stretched along the x axis or the y axis depending on the relative values of the initial perturbation velocities U and V.

The important result is that the plasma flattens and expands radially perpendicular to the z axis while the plasma kinetic energy and the current density increase without limit.

The MHD equations can also be solved if the plasma is considered to be a perfect gas with a finite electrical conductivity. At the finite cumulation time, the plasma initially contained within a circular cross section plasma would be squeezed within an ellipse of zero volume. The density, velocity V_y , current density j_z , as well as the internal kinetic or magnetic energies, all become infinite inside the limiting segments.

The cumulation process requires an energy source supplied by the energy stored in the magnetic field. An interesting consequence of the cumulation process is that the electron

velocity J/n tends to infinity which explains the process of acceleration of particles to extremely high velocities as is observed in cosmic ray particles.

The hot plasma in the magnetic field would generate high energy radiation in the form of synchrotron radiation.

16. MAGNETIC FIELD ANNIHILATION MODEL FOR GRBs

The large acceleration and radiation and radiation can be explained by the help of a model of magnetic fields annihilation.

The annihilation process can result from a fast rotating neutron star or be generated in a fusion of a neutron star with a black hole. A compact rotating object with a magnetic field produces an electromagnetic wave comparable to an antenna.

If the plasma is expelled by the central object, in the outward traveling wave regions could contain oppositely aligned magnetic fields. Through the generation of instabilities, plasma components in which the magnetic field orientations are in opposite directions can come close to each other. As a result the magnetic field annihilates and the magnetic energy is released and transferred to the plasma. Figure 9 illustrates the principle of the field annihilation.

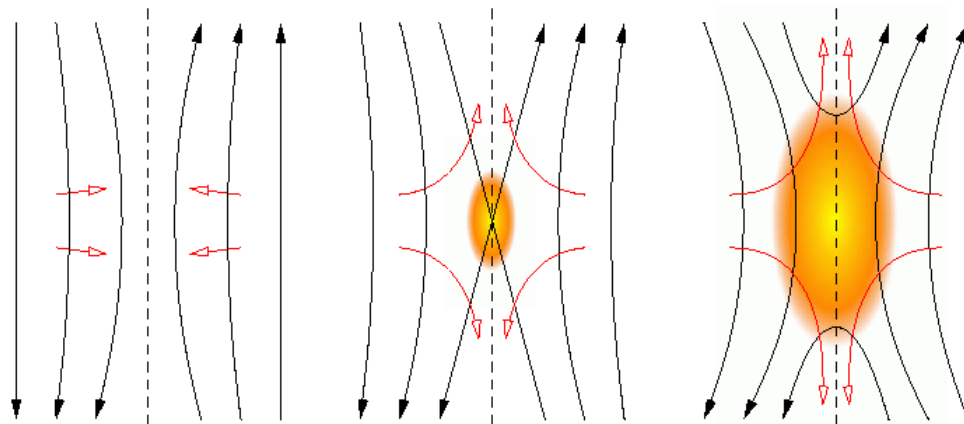


Figure 9. Two dimensional sketch of the magnetic field annihilation.

At the intersecting point, the magnetized plasma outflow is not only strongly accelerated but also heated up.

17. ENERGETIC RADIATION IN THUNDERSTORMS

In the physics of thunderstorms and lightning, large electric fields initiate lightning and affect its propagation. Enormous bursts of energetic radiation occur in thunderstorms in the form of electrons, x and gamma rays caused by strong electric fields in the air. These bursts generate runaway electrons that rapidly discharge the electric fields.

Runaway electrons are produced in air when the energy gained from the electric field exceeds the loss from collisions. This allows the electrons to accelerate to relativistic energies. An avalanche of such runaway electrons develops when energetic knock off electrons are produced by hard elastic or Moeller scattering with electrons in the air molecules. The knock off

electrons subsequently run away producing more energetic knock off electrons and so on providing positive feed back to the avalanche.

The runaway electrons in the avalanche produce large quantities of ionization and x and gamma rays through bremsstrahlung interactions with air. Gamma rays here are of atomic not nuclear origin and are just highly energetic x rays with energies in the MeV range.

The high energy gamma rays generate a small number of positrons through the process of pair production, some of which also run away, but in the opposite direction of the electrons in the Earth's magnetic field. These then interact with ordinary electrons producing annihilation radiation gamma rays.

Bremstrahlung gamma rays are produced when the runaway electrons collide with air. Additional seed electrons are generated by two feedback mechanisms producing more runaway breakdown. These feedback mechanisms include positrons feedback and gamma ray feedback through Compton scattering or the photoelectric effect.

The existence of runaway breakdown correlates with observations of energetic radiation associated with natural and triggered man made lightning experiments, thunderstorms, and red sprites.

18. TERRESTRIAL GAMMA RAYS FLASHES, TGFs

Using the Compton Gamma Ray Observatory, CGRO, bursts of Terrestrial Gamma Ray Flashes, TGFs were first observed in 1994. The TGFs occur relatively high in the atmosphere and are not from the same sources of gamma rays seen on the ground. About 15 to 20 events are observed per month.

Prior to 1994, it was thought that bursts of gamma rays had an astrophysical origin only. The photon energies exceeding 1 MeV suggest that the gamma rays are produced by the bremsstrahlung radiation from accelerated high energy electrons, since this type of radiation is emitted when electrons are scattered by nuclei. The upward beams of runaway electrons follow the Earth's magnetic field, and are thought to be accelerated by thundercloud fields. These flashes are considered to be the most energetic natural phenomenon on Earth.

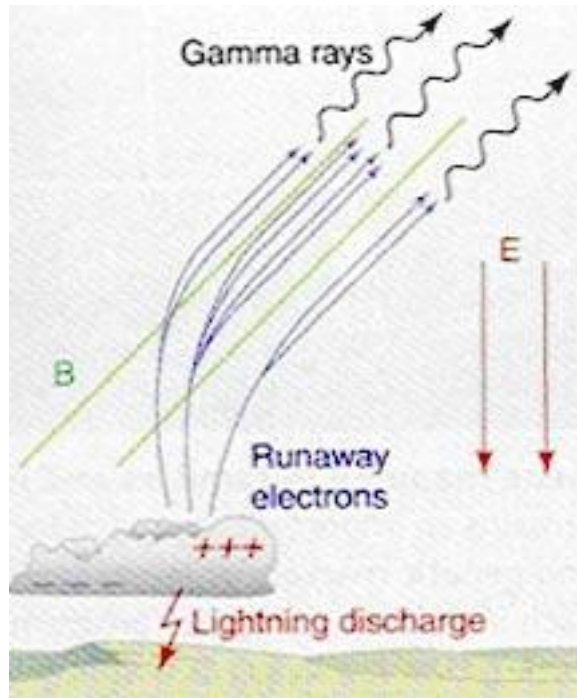


Figure 10. Terrestrial gamma rays flashes formation from lightning strikes.

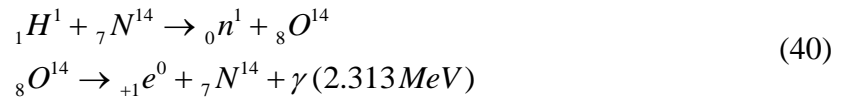
Further observations by the Reuven Ramaty High Energy Solar Spectroscopic Imager, RHESSI satellite in 2005 showed that these flashes are common and that the photon energies can reach 20 MeV. Seed electrons at relativistic energies above 1 MeV are accelerated in an electric field, followed by electrical breakdown as a result of their collisions with the air molecules. These relativistic runaway breakdowns can proceed at much lower electric fields than the conventional air breakdowns in which the ambient thermal electrons are accelerated to energies sufficient to ionize nitrogen in the air. A runaways beam of 100 keV to 10 MeV would radiate gamma rays at altitudes of 30-70 kms. For the electrons with an energy exceeding 500 keV, the loss in energy due to scattering is insignificant above 70 kms because of the low air density. Thus most of the particles must escape into the radiation belts resulting in an injected beam with a fluence of 10^6 to 10^7 [electrons/cm²]. In cloud to ground discharges the transverse scale of the beam is from 10 to 20 kms. For cloud to cloud discharges, it may be as large as 100 kms. The beam duration is just about 1 millisecond.

Transient intense electric fields associated with thunderclouds create a total potential drop at an altitude between 20 to 80 kilometers of more than 30 mega volts, MV for large positive cloud to ground discharges. These strong electric fields produce nonlinear runaway avalanches of accelerated electrons which collide with the air molecules stripping in the process an even larger number of relativistic electrons. A large number of relativistic electrons spreads over a large region generating the TGFs at an altitude of 30 to 70 kms.

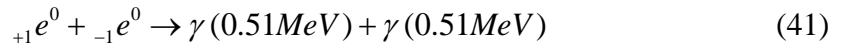
The intense upward moving electrons enter the Earth's Van Allen radiation belts of charged particles trapped in the Earth's magnetic field. Some of them may become trapped there and then discharged in conjugate regions of the Earth where intense lightning discharges occur such as in the Southern Hemisphere from a Northern Hemisphere thunderstorm. There, they interact with the air molecules in the denser atmosphere creating optical emissions and x rays. The electrons could drift around the planet and could precipitate into the atmosphere near the

South Atlantic anomaly off the coast of Brazil, where the Earth's magnetic field exhibits a minimum.

It is not clear what the dose to persons on the ground from these TGFs is. Experimental and theoretical investigations of the gamma ray dose effects of the TGFs during thunderstorms remains to be undertaken. If water in the clouds is dissociated into oxygen and hydrogen, the accelerated protons could be emitted and they could interact through nuclear reactions with nitrogen in the atmosphere, for instance through the (p, n) reaction:



which can also lead to the generation of gamma photons, albeit from a nuclear rather than an electronic process:



The neutrons can also interact with other isotopes in the atmosphere, such as through the (n, p) reaction:



which would contribute to the creation of carbon¹⁴ in the Earth's atmosphere in addition to the production from cosmic ray neutrons. If taken into account it would affect the results of carbon dating measurements of archaeological artifacts by suggesting a higher level of equilibrium C¹⁴ concentration in the Earth's atmosphere.

19. GAMMA-RAY BUBBLES

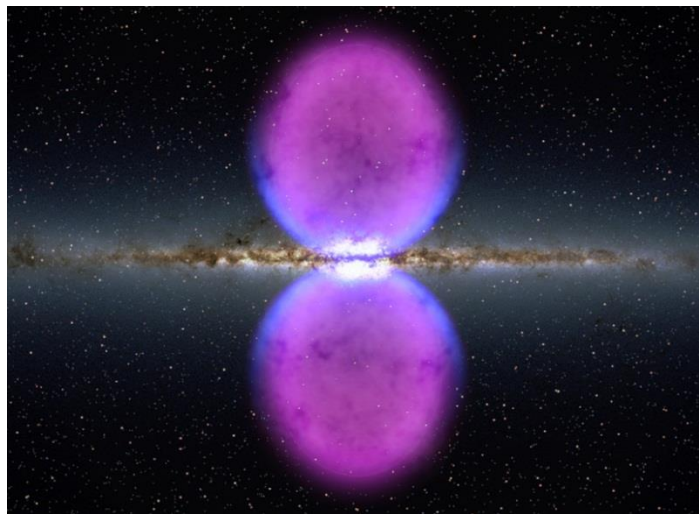


Figure 11. Gamma rays bubbles from eruption of massive black hole at center of the Milky-way Galaxy.

An ancient eruption of a super-massive black hole in the Milky Way may have inflated two huge bubbles of gamma rays which are considered a new type of astronomical object.

Combined, the bubbles, which are aligned at the center of the Milky Way, span a vast distance of about 50,000 light-years. The structures are very distinct, with defined edges, and have as much energy in them as 100,000 supernovae.

They were found with NASA's Fermi Gamma-Ray Telescope, which surveys the sky every three hours for the highest-energy light.

Among the 1,500 sources of gamma rays Fermi has mapped so far, nothing resembles the bubble-shaped structures, which stretch across more than half of the visible sky, from the constellation Virgo to the constellation Crux.

Scientists have two possible explanations for the gamma ray bubbles. The first theory suggests a burst of star-formation at the center of the galaxy generated short-lived massive stars with energetic winds that blasted high-energy particles out into space.

The alternative theory is an outburst from the supermassive black hole lurking in the center of the galaxy.

In other galaxies, astronomers have seen evidence for jets of particles triggered by matter that is being pulled into a black hole.

There is no evidence that the Milky Way's central black hole, which is about 400 million times more massive than the sun, has jets, but astronomers suspect it might have in the past.

This might be the first evidence for a major outburst of the black hole at the center of the galaxy. When it is going full blast, it would take 10,000-100,000 years for it to produce enough energy to create these structures.

These features could reveal unexpected physical processes in our galaxy that until now we knew nothing about despite the fact that these features could possibly be almost as large as the Milky Way and might have been around for millions of years.

20. GAMMA RAY BURSTS, COLLIDING NEUTRON STARS

Neutron stars are dense leftovers from the stellar explosions known as supernovae. Supernovae are what seeded a hydrogen-rich universe with heavier elements fused in the stars' cores, like carbon, oxygen or iron. But unlike carbon or iron, the heavier elements such as uranium and gold cannot be synthesized in the heart of a star, so its origin has remained some sort of a mystery.

In the search for short gamma-ray bursts which are flashes of high-energy radiation that signal powerful explosions that can come from billions of light-years away in the past, it was discovered that some of them are long, lasting even a few minutes, and others are incredibly short at fractions of a second, making them very difficult to observe.

In a short gamma ray burst designated as GRB 130603B, identified by NASA's Swift satellite, which lasted 2/10s of a second and captured with the powerful Magellan/Baade telescope in Chile, it appeared that it was originating from the collision of two neutron stars, each roughly the size of Austin, Texas, and filled with 1.5 times the mass of the sun. The impact resulted in a black hole and the short bright burst of gamma rays that was observed.

GRB 130603B also displayed a strange glow of infrared radiation that the astrophysicists realized was coming from the heavy elements like lead, thorium, and uranium, some decaying radioactively and thus producing the infrared light. The explosion had been responsible for the creation of a whole zoo of heavy elements that is estimated to be an equivalent to 1 percent of the sun's matter

being flung out from the collision in a tail, and about 10 parts per million of that tail was made of gold. This exploding star system is 3.9 billion light-years away or in the past [10].

EXERCISE

1. Compare the thicknesses of the following different materials that would attenuate a narrow beam of 1 MeV gamma-rays in “good geometry” with a build-up factor of unity to one millionth of its initial strength, given their linear attenuation coefficients in cm^{-1} :

Material	Density [gm/cm^3]	Linear attenuation coefficient, μ at 1 MeV, [cm^{-1}]
Pb	11.3	0.771
H ₂ O	1	0.071
Concrete	2.35	0.149

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