NUCLEAR AND PARTICLE PHYSICS
(PH242)

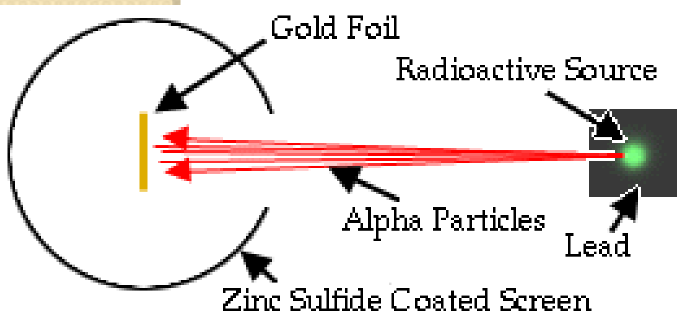
PARTICLE PHYSICS

History of Elementary Particles

THE CLASSICAL ERA (1897-1932)

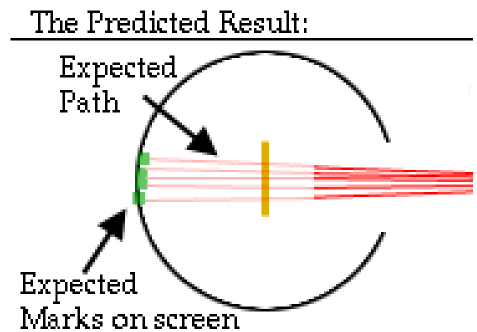
- Elementary particle physics was born in 1897 with J.J. Thomson's discovery of the ELECTRONS
- Rutherford's Gold foil scattering experiment concluded that the positive charge (and virtually all of the mass) was concentrated at the center, occupying only a tiny fraction of the volume of the atom.
- The nucleus of the lightest atom (hydrogen) was given the name PROTON by Rutherford.
- In 1914, Neils Bohr proposed a model for hydrogen consisting of a single electron circling the proton.
- In 1932 Chadwick discovered the NEUTRON, an electrically neutral twin to proton.
- Thus in 1932, it was all just protons, neutrons and electrons which constituted the matter

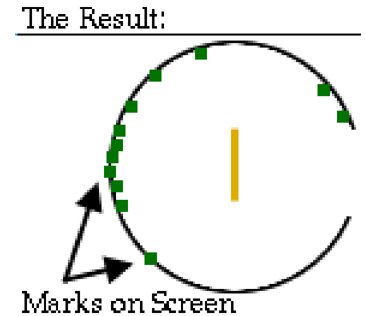
Rutherford's Scattering Expt



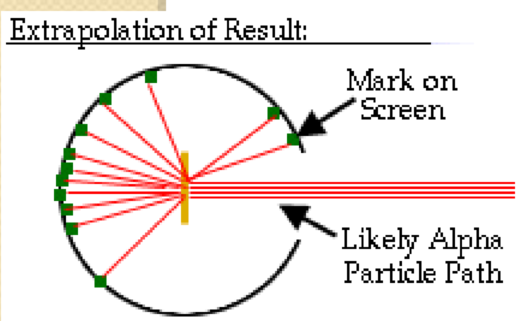
Apparatus

Hypothesis

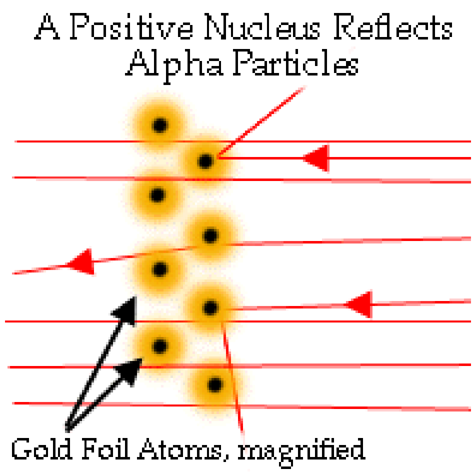




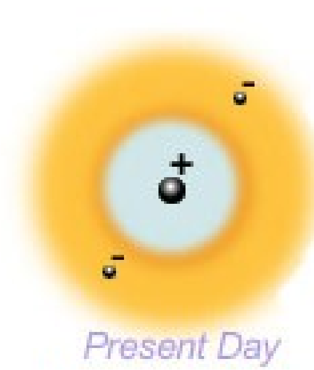
Results (data)



Analysis



Conclusion: A Nucleus!



DISCOVERY OF THE NEUTRON (Chadwick, 1932)

Neutron: a particle with mass ≈ proton mass
but with zero electric charge

Nucleus with atomic number *Z* and mass number *A*:
a bound system of *Z* protons and (*A* – *Z*) neutrons

Neutron source in Chadwick's experiments: a ^{210}Po radioactive source (5MeV α – particles) mixed with Beryllium powder ⇒ emission of electrically neutral radiation capable of traversing several centimetres of Pb:

$$^{4}He_{2} + {}^{9}Be_{4} \rightarrow {}^{12}C_{6} + \text{neutron}$$

↑
α - particle

THE PHOTON (1900-1924)

- First contribution to the discovery of PHOTONS was made by Planck in 1900
- Planck explained the blackbody radiation spectrum assuming that the electromagnetic radiation is quantized (i.e., in the form of small packages)
- Einstein in 1905 argued that quantization was a feature of the electromagnetic field itself, having nothing to do with the emission mechanism
- With this new twist, Einstein adapted Planck's idea to explain the photoelectric effect.

MESONS (1934-1947)

- What holds the nucleus together?
- A force must be present, more powerful that the electrical repulsion, that binds the protons (and neutrons) together.
- Physicists called it simply THE STRONG FORCE.
- First significant theory of strong force was proposed by Yukawa in 1934.
- Yukawa assumed that the protons and neutrons are attracted to the nucleus by some sort of field, the quantum of which, the particle whose exchange accounts for the known features of the force.

- Yukawa calculated that its mass should be nearly 200 times that of electron or about a sixth the mass of a proton

- Since it fell between the electron and proton, Yukawa’s particle came to be known as the MESON (meaning “middle weight”)

- 1n 1937, two separate groups identified particles matching Yukawa’s description in cosmic rays.

- In 1947, Powell and his co-workers discovered two middle-weight particles in cosmic rays, which they called PIONS and MUONS

- PION is known as the true Yukawa Meson.

PIONS

- There are three varieties of pions
  - π^+ and π^-
    - Mass of 139.6 MeV/c^2
  - π^0
    - Mass of 135.0 MeV/c^2
- Pions are very unstable
  - For example, the π^- decays into a muon and an antineutrino with a lifetime of about 2.6 x10^{-8} s

MUONS

- Two muons exist
  - μ^- and its antiparticle μ^+
- The muon is unstable
  - It has a mean lifetime of 2.2 μs
  - It decays into an electron, a neutrino, and an antineutrino

ANTIPARTICLES (1930-1956)

- Every particle has a corresponding antiparticle
  - From Dirac’s version of quantum mechanics that incorporated special relativity
- An antiparticle has the same mass as the particle, but the opposite charge
- The positron (electron’s antiparticle) was discovered by Anderson in 1932
  - Since then, it has been observed in numerous experiments
- Practically every known elementary particle has a distinct antiparticle
  - Among the exceptions are the photon and the neutral pi particles

Dirac’s Explanation of antiparticles

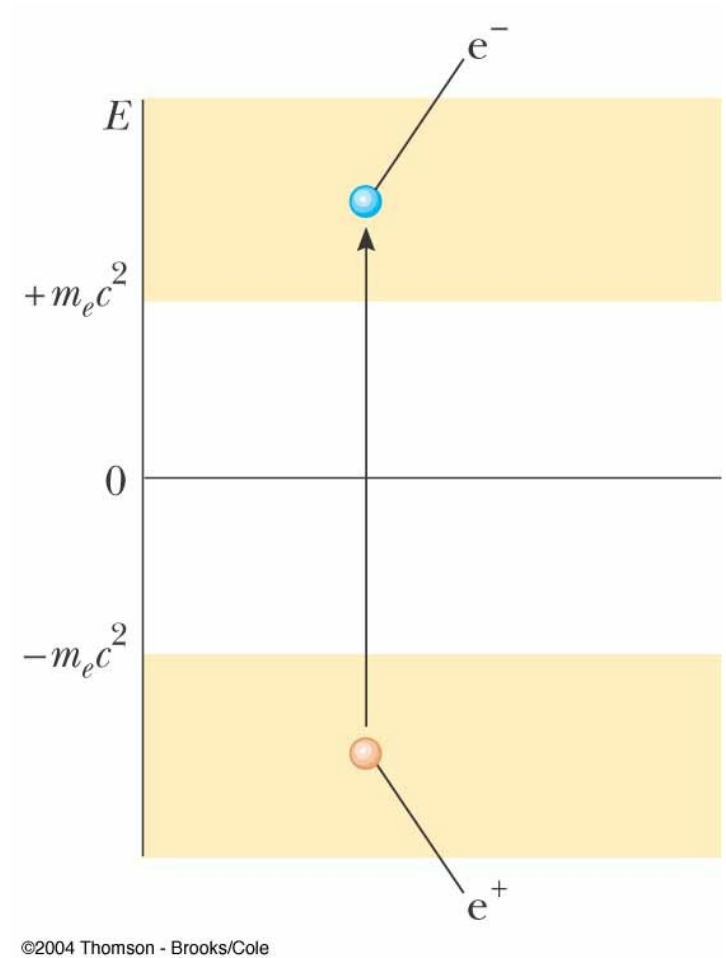
- The solutions to the relativistic quantum mechanic equations required negative energy states

- Dirac postulated that all negative energy states were filled
  - These electrons are collectively called the *Dirac sea*

- Electrons in the Dirac sea are not directly observable because the exclusion principle does not let them react to external forces

Dirac’s Explanation (continued)

- An interaction may cause the electron to be excited to a positive energy state
- This would leave behind a hole in the Dirac sea
- The hole can react to external forces and is observable



Dirac’s Explanation (continued)

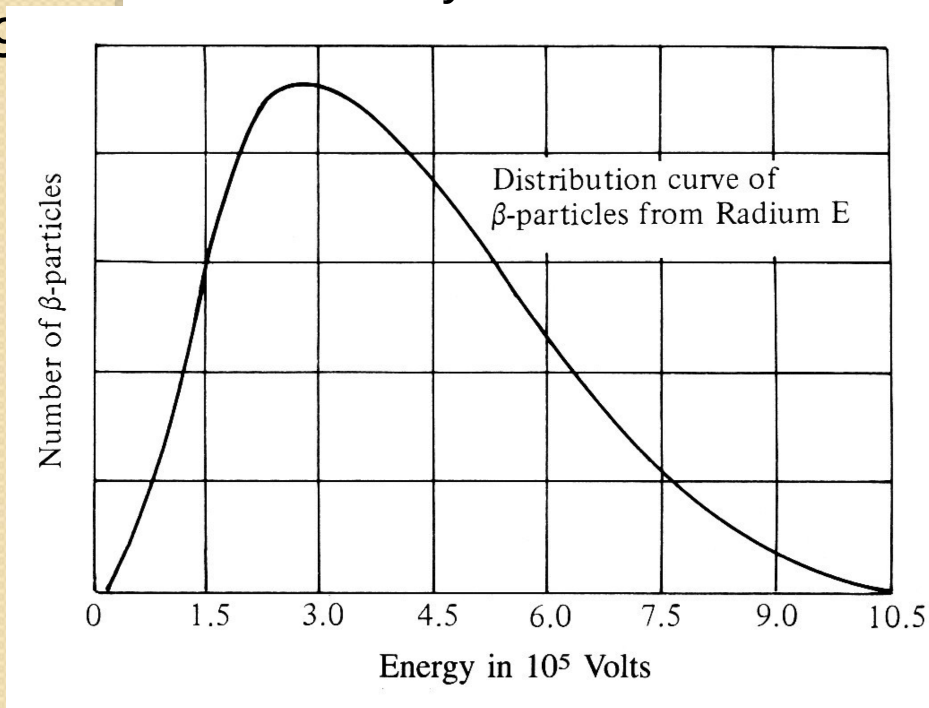
- The hole reacts in a way similar to the electron, except that it has a positive charge

- The hole is the *antiparticle* of the electron
  - The electron’s antiparticle is now called a *positron*

NEUTRINOS (1930-1962)

A puzzle in β – decay: the continuous electron energy spectrum

First measurement by Chadwick
(19



Radium E: $^{210}Bi_{83}$
(a radioactive isotope
produced in the decay
chain
of ^{238}U)

If β – decay is $(A, Z) \rightarrow (A, Z+1) + e^-$, then the emitted electron is mono-energetic:

electron total energy $E = [M(A, Z) - M(A, Z+1)]c^2$

(neglecting the kinetic energy of the recoil nucleus $\frac{1}{2}p^2/M(A,Z+1) << E$)

Several solutions to the puzzle proposed before the 1930's (all wrong),
including
violation of energy conservation in β – decay

December 1930: public letter sent by W. Pauli to a physics meeting in Tübingen

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

...because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous β-spectrum, I have hit upon a desperate remedy to save the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin ½ and obey the exclusion principle ..... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous β-spectrum would then become understandable by the assumption that in β-decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant .... For the moment, however, I do not dare to publish anything on this idea ......So, dear Radioactives, examine and judge it. Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zürich because of a ball on the night of 6/7 December. ....

W. Pauli

NOTES

- Pauli's neutron is a light particle ⇒ not the neutron that will be discovered by Chadwick one year later
- As everybody else at that time, Pauli believed that if radioactive nuclei emit particles, these particles must exist in the nuclei before emission

Theory of β-decay

(E. Fermi, 1932-33)

– β^- decay: $n \rightarrow p + e^- + \nu$
β^+ decay: $p \rightarrow n + e^+ + \nu$ (e.g., $^{14}O_8 \rightarrow {}^{14}N_7 + e^+ + \nu$)

ν: the particle proposed by Pauli
(named "neutrino" by Fermi)
ν: its antiparticle (antineutrino)

Fermi's theory: ⇒ particles emitted in β – decay need not exist before emission –

they are "created" at the instant of decay

Neutrino must be present to account for conservation of energy and momentum

$$n_0^1 \rightarrow p_1^1 + e_{-1}^0 + \bar{\upsilon}_0^0$$

- Large variations in the emission velocities of the β particle seemed to indicate that both energy and momentum were not conserved.
- This led to the proposal by Wolfgang Pauli of another particle, the neutrino, being emitted in β decay to carry away the missing mass and momentum.
- The neutrino (little neutral one) was discovered in 1956.

Calculate the energy released in the reaction

$$n_0^1 \rightarrow p_1^1 + e_{-1}^0 + \bar{v}_0^0$$

1.008665 u **1.007825 u** **0.0005486 u**

1 u = 1.660×10^{-27} kg

1 J = 1.6×10^{-19} eV

Calculation

Mass difference $= 1.008665 - (1.007825 + 0.0005486)$

$= 0.0002914$ u

$= 0.0002914 \times 1.660 \times 10^{-27}$ kg

$= 4.83724 \times 10^{-31}$ kg

Calculation

$$E = mc^2$$

$$= (4.83724 \times 10^{-31})(3.0 \times 10^{8})^{2} \text{ J}$$

$$= 4.353516 \times 10^{-14} \text{ J}$$

$$= \frac{4.353516 \times 10^{-14}}{1.602 \times 10^{-19}} = 271755 \text{ eV}$$

$$= 0.272 \text{ MeV}$$

It has been found by experiment that the emitted beta particle has less energy than 0.272 MeV
Neutrino accounts for the ‘missing’ energy

STRANGE PARTICLES (1947-1960)

- Some particles discovered in the 1950's were found to exhibit unusual properties in their production and decay and were given the name *strange particles*

- Peculiar features include

  - Always produced in pairs

  - Although produced by the strong interaction, they do not decay into particles that interact via the strong interaction, but instead into particles that interact via weak interactions

    - They decay much more slowly than particles decaying via strong interactions

Examples of decay modes

$K^{\pm} \rightarrow \pi^{\pm}\pi^{\circ}$; $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$; $K^{\pm} \rightarrow \pi^{\pm}\pi^{\circ}\ \pi^{\circ}$; $K^{\circ} \rightarrow \pi^{+}\pi^{-}$; $K^{\circ} \rightarrow \pi^{\circ}\ \pi^{\circ}$; . . .
$\Lambda \rightarrow p\ \pi^{-}$; $\Lambda \rightarrow n\ \pi^{\circ}$; $\Sigma^{+} \rightarrow p\ \pi^{\circ}$; $\Sigma^{+} \rightarrow n\ \pi^{+}$; $\Sigma^{+} \rightarrow n\ \pi^{-}$; . . .
$\Xi^{-} \rightarrow \Lambda\ \pi^{-}$; $\Xi^{\circ} \rightarrow \Lambda\ \pi^{\circ}$

QUARKS (1964)

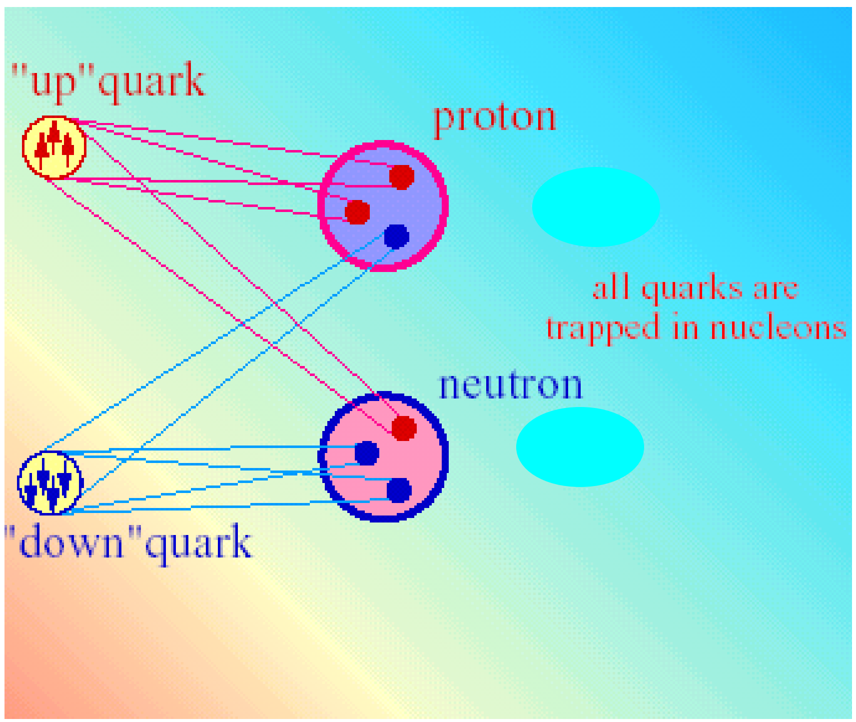
- Hadrons are complex particles with size and structure
- Hadrons decay into other hadrons
- There are many different hadrons
- Quarks are proposed as the elementary particles that constitute the hadrons
    - Originally proposed independently by Gell-Mann and Zweig

Quarks

Fundamental building block of baryons and mesons

$Q = +\frac{2}{3}$

$Q = -\frac{1}{3}$



$Q = +1$

$Q = 0$

The six quarks

Quarks

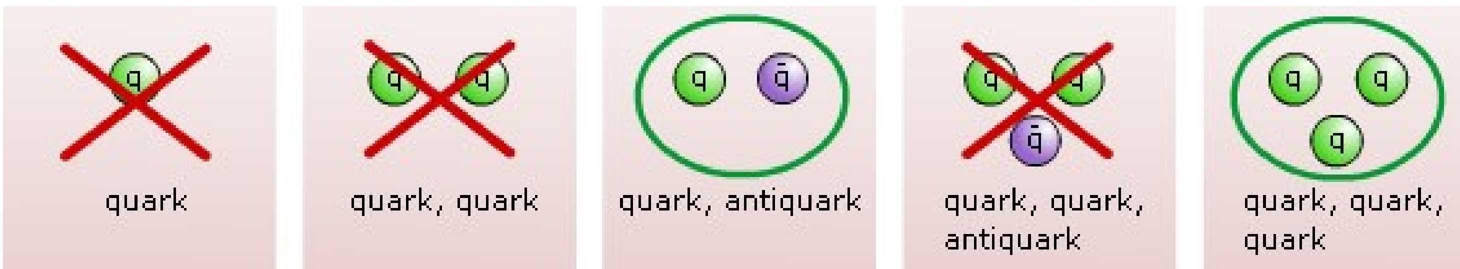
- Most of the matter we see around us is made from protons and neutrons, which are composed of up and down quarks.

- There are six quarks, but physicists usually talk about them in terms of three pairs: up/down, charm/strange, and top/bottom. (Also, for each of these quarks, there is a corresponding antiquark.)

- Quarks have the unusual characteristic of having a fractional electric charge, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called color charge.

Color charge of quarks (1)

- So one had to explain why one saw only those combinations of quarks and antiquarks that had integer charge, and why no one ever saw a q, qq, qqqbar, or countless other combinations.

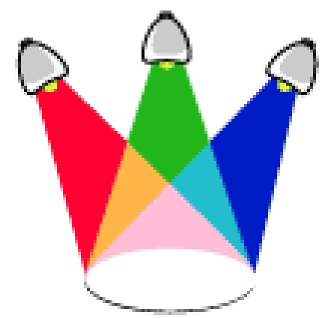


- Gell-Mann and others thought that the answer had to lie in the nature of forces between quarks. This force is the so-called "strong" force, and the new charges that feel the force are called "color" charges, even though they have nothing to do with ordinary colors.

Color charge of quarks (2)

- They proposed that quarks can have three color charges. This type of charge was called "color" because certain combinations of quark colors would be "neutral" in the sense that three ordinary colors can yield white, a neutral color.
- Only particles that are color neutral can exist, which is why only qqq and q q-bar are seen.
- This also resolve a problem with Pauli principle

Just like the combination of red and blue gives purple, the combination of certain colors give white. One example is the combination of red, green and blue.



Units in particle physics

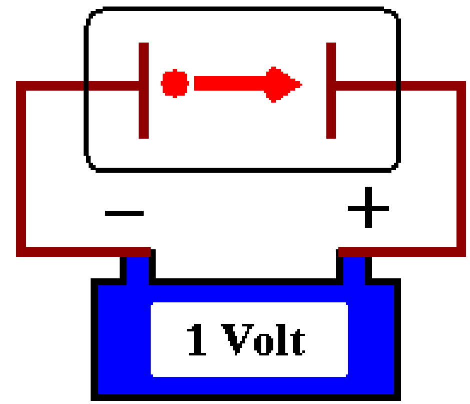
Energy

1 electron-Volt (eV):

the energy of a particle with electric charge = |*e*|,

initially at rest, after acceleration by a difference of electrostatic potential = 1 Volt

(*e* = 1.60 x □□ $^{-19}$ C)



□ eV = □.□□ x □□ $^{-19}$ J

Multiples:

1 keV = 10^{3} eV ; □ MeV = □□^{6} eV

□ GeV = □□$^{□}$ eV; □ TeV = □□^{12} eV

Energy of a proton in the LHC (in the year 2007):

□ TeV = □.□□ x □□ $^{-□}$ J

(the same energy of a body of mass = □ mg moving at speed = 1.5 m /s)

How do you produce elementary particles?

1. Cosmic Rays

- The earth is constantly bombarded with high-energy particles coming from outer space.
- When they hit atoms in the upper atmosphere, they produce showers of secondary particles (mostly muons).

As a source of elementary particles, cosmic rays have 2 **advantages**, viz.,

- They are free
- Their energies can be enormous

But, they have 2 major **disadvantages**, viz.,

- The rate at which they strike any detector of reasonable size is

2. Nuclear Reactors

- When a radioactive nucleus disintegrates, it may emit a variety of particles namely, neutrons, neutrinos, alpha particles, beta rays, gamma rays, etc..

- Alpha particles (rays) are bound states of 2 neutrons plus 2 protons (Helium nuclei)

- Beta particles (rays) are electrons or positrons

- Gamma rays are photons

3. Particle accelerators

- The method involves accelerating the electrons or protons and smashing them into a target.
- The new stream of particles produced can be separated out by using different absorbers and magnets.
- An intense secondary beam of positrons, muons, pions, kaons, and antiprotons can be produced, which in turn can be fired at another target.
- The stable particles, electrons, protons, positrons and antiprotons can even be fed into giant storage rings (guided by powerful magnets) to be extracted and used at required moment.