Elementary Particles and Cosmic radiation

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JOL-2015
Basic elementary particles

Three types of basic elementary particles have been known for a long time. They are the building blocks of normal atoms:

- Electrons; $e^-$, in the electron shell
- Protons; $p^+$, in the nucleus – defines the element
- Neutrons; $n$, uncharged – stabilizes the nucleus by ”diluting” the positively charged protons.
Beta-decay energy

All nuclear decay reactions are quantified. Hence a specific beta-decay should always produce beta particles with the same energy. However, this is what is observed. $E_{\text{max}}$ is the beta-decay energy.

Where does the missing energy go?
Neutrinos

*I have done a terrible thing today, something no theoretical physicist ever do. I have suggested something that can never be verified experimentally.*

W. Pauli, 4 dec. 1930.

The neutrino explained the electron energy in beta decay. It also gave a plausible explanation of how the beta particle could be formed by the atomic nucleus, and it explained why it looked like as if energy disappeared without trace in the beta decay of a nucleus.

Neutrinos are generated in the sun by e.g.: \( p + p \rightarrow d + e^+ + \nu \)

The intensity of neutrinos on Earth is estimated to be \( 10^{15} \text{ m}^{-2}\text{s}^{-1} \). Of these, about 85 % is from the reaction above.

Pauli never believed that it would be possible to detect a neutrino. Several light-years of lead would be needed to stop it (1 ly \( \sim 10^{16} \text{ km} \)). The reason we can detect neutrinos is through their reaction with other matter. Most commonly used is: \( ^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}(\text{EC, 35d})^{37}\text{Cl} \). Separated Ar is detected by its decay.

The neutrino is the most common particle in the Universe. It is 10 times more common than photons, which in their turn is \( 10^9 \) times more common than protons and neutrons. It is designated by \( \nu \) (greek n).
Neutrinos cont.

Measurements by the Cl-method show that the neutrino flux on Earth from the sun is only 1/3 of the theoretically expected value. The reason is that some neutrinos change type during passage out through the sun. Verified by new measurements using D$_2$O detector in Canada which can measure lower $\nu$-energies.

At 07.35.35 GMT on 23$^{rd}$ February 1987 a strong neutrino pulse was recorded by several detectors. About 18 hours later it was seen that a supernova had exploded, SN1987A.

The delay of light is caused by the very small amount of matter in interstellar space. Hence, the speed of light in interstellar space was less than $c_o$.

Because the neutrinos move with the speed of light, $c_o$, they arrived before the photons.

There is at least three types – Flavors - of neutrinos: electron neutrinos, muon neutrinos, and tauon neutrinos. The neutrino oscillates between the three flavors by trading mass and kinetic energy.
Oscillation probabilities for an initial electron neutrino

FLAVORS: black = e-neutrino, blue = muon-neutrino, and red = tau-neutrino
Oscillation probabilities for an initial muon neutrino

FLAVORS: black = e-neutrino, blue = muon-neutrino, and red = tau-neutrino
FLAVORS: black = e-neutrino, blue = muon-neutrino, and red = tau-neutrino
The Neutrino Observatory in Sudbury
2 km below surface, contains $10^6$ kg $D_2O

The Sudbury Neutrino Observatory has proven, almost beyond doubt, that neutrinos switch flavour - solving the solar neutrino problem. Pictured is the detector under construction. Image: SNO.
The Dirac wave equation and antimatter

The well known Schrödinger equation is only valid in a universe where the speed of light is infinite (i.e. m is constant at any speed). In 1928 Dirac published a new wave equation which is valid in a relativistic universe where the speed of light is finite.

\[
\left( i \gamma^\mu \frac{\partial}{\partial x^\mu} - \frac{mc}{\hbar} \right) \psi(x) = 0
\]

The solution of this equation for the rest energy of an electron is a square root of a number of variables. Initially only the root which gave a positive rest mass was accepted. However, Dirac realized that the negative root could describe a universe with all particle positions filled, but at negative rest mass. Addition of sufficient energy to a point could then produce a particle with positive mass and a hole in the negative mass matter. A particle and its antiparticle were then formed as a pair. The first antiparticle, $\beta^+$, was discovered $\sim2$ y later.
The solution of the Dirac wave equation for the total energy, \( W \), of a free electron looks formally as follows (from my old Swedish textbook in nuclear chemistry);

\[
W = \pm c \sqrt{p_1^2 + p_2^2 + p_3^2 + m^2 c^2}
\]

where the \( p \):s are parameters, \( c \) the speed of light in vacuum, and \( m \) the electron mass.

Hence, it is believed today that any kind of particle has a corresponding antiparticle. In special cases, the particle is its own antiparticle (e.g. photon).

Solutions to the Dirac equation are 4-dimensional wave functions, and elementary particles have no intrinsic spin.
Elementary Particles (disregarding Dirac)

Fermions: matter particles (have spin $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, …)

baryons: can feel the strong interaction

Quarks: up, down, charm, strange, top, bottom quarks and their anti-particles

leptons: does not feel the strong interaction

electron, muon, tachyon, their neutrinos and anti-particles

Bosons (force carriers)

with spin 1, 2, …

gravitons, photons, W-bosons, Z-bosons, gluons, Mesons

with spin 0

Higgs particle(s) (give the other particles their mass)
# Elementary Particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Rest Mass (u)</th>
<th>Charge (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up Quark</td>
<td>1/3</td>
<td>+2/3</td>
</tr>
<tr>
<td>Down Quark</td>
<td>1/3</td>
<td>-1/3</td>
</tr>
<tr>
<td>Charm Quark</td>
<td>1.61</td>
<td>+2/3</td>
</tr>
<tr>
<td>Strange Quark</td>
<td>0.54</td>
<td>-1/3</td>
</tr>
<tr>
<td>Topp Quark</td>
<td>188.5</td>
<td>+2/3</td>
</tr>
<tr>
<td>Bottom Quark</td>
<td>4.83</td>
<td>-1/3</td>
</tr>
<tr>
<td>$\nu_e$ (electron neutrino)</td>
<td>&lt; 2x10^{-8}</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_\mu$ (muon neutrino)</td>
<td>~ 0</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_\tau$ (tauon neutrino)</td>
<td>~ 0</td>
<td>0</td>
</tr>
<tr>
<td>e (electron)</td>
<td>0.0005486</td>
<td>-1</td>
</tr>
<tr>
<td>$\mu$ (muon)</td>
<td>0.114</td>
<td>-1</td>
</tr>
</tbody>
</table>
The "Standard Model"

Proton = 2 up-quarks + 1 down-quark
Charge = 2 x +2/3 – 1 x (-1/3) = +1
Mass = 2 x 1/3 + 1 x 1/3 = 1

Neutron = 1 up-quark + 2 down-quarks
Charge = +2/3 – 2 x (-1/3) = 0
Mass = 1 x 1/3 + 2 x 1/3 = 1
Neutron beta-decay
Many Worlds Interpretation of Wave Function Collapse

In his thesis 1957 Hugh Everett showed that the derivation of the general relativity theory by Einstein implicitly assumed that the observer is outside of our universe. When the observer inside the universe the solutions are slightly different.

One possible interpretation of these solutions is that the universe "splits" each time a probabilistic quantum event occur.

This removes many problems e.g. Schrödinger's cat experiment, the EPR paradox, von Neumann's "boundary problem", and even the wave-particle duality. Quantum cosmology also becomes intelligible, since there is no need any more for an observer outside of the universe.
Forces in Nature

Gravity
Acts between all matter
Additive and always attractive
Infinite range
 Probably no saturation (Black Holes)
Transmits at the speed of light
F = km₁m₂/r² with $6.673 \cdot 10^{-11}$ m³/kg·s²

Strong Interaction
Acts between hadrons (baryons, mesons)
Saturates
Short range, <10⁻¹⁴ m
Transmits rapidly (action time <10⁻²³ s)
Exists inside the atomic nucleus

Electromagnetic Force
Acts between charged bodies
Additive, but attractive and repulsive
Infinite range
Saturates perhaps?
Transmits at the speed of light
F = -kz₁z₂/r², k depends on the medium

Weak Interaction
Acts on leptons (e, muons, neutrinos)
Also acts between leptons and hadrons
Slow action, 10⁻⁹ s
Limited range, 10⁻¹⁵ m

Dark energy
???
### Forces in Nature

#### Relative Strengths

1. Gravity
   - Force: $1 \times$ gravity

2. Weak interaction
   - Force: $10^{25} \times$ gravity

3. Electromagnetic force
   - Force: $10^{36} \times$ gravity

4. Strong interaction
   - Force: $10^{38} \times$ gravity

5. Dark energy
   - Force: $? \times$ gravity

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Dark energy only acts over enormous distances and its strength might vary with time. At present it increases the expansion rate of the Universe, and opposes gravity over very large distances.
Cosmic radiation

In 1911 V. F. Hess discovered that background radiation increased with altitude when he sent up a radiation detector in a balloon. Hence it was found out that background radiation not only originates from radioactive elements on Earth but also arrives from space – cosmic radiation. It was soon discovered that the intensity of the cosmic radiation varies both with altitude and place on Earth.

Map of intensity variations in the cosmic background radiation from COBE satellite data. The hot red band across the equator is the plane of our galaxy. Fluctuating emissions from the edge of the visible universe dominate regions away from the equator. Courtesy: NASA
Cosmic Radiation

In order to describe the cosmic radiation, it is important to differentiate between primary and secondary radiation.

**Primary radiation** is: Electromagnetic radiation

Particle radiation

Neutrinos

**Secondary radiation**: When primary radiation hits the atmosphere as particles or photons it gives rise to a large number of secondary particles due to its very high initial energy. The majority of initial secondary particles are pions. They are short-lived and decay into muons and pions.

Cosmic radiation creates 2-3 ion pairs per cm$^3$ and s at the Earth’s surface (varies during the sunspot cycle).
FROM THE SUN
Non-isotopic particle flux
Flux dependent on solar activity
All masses (mainly $^1$H, also $^3$H)
Energies $< 10^4$ GeV
Minor fraction

FROM GALAXIES
Isotropic particle flux
Flux independent of solar activity
All masses (mainly $^1$H, no $^3$H)
Energies $10^4$ - $10^{10}$ GeV
Major fraction

EARTH'S ATMOSPHERE (N$_2$, O$_2$, Ar, etc) AT ABOUT 25 KM

Neutrinos
Formation of pions
Direct ionization
Spallation reactions

$\nu \rightarrow \pi^+ \rightarrow \mu^+$
$\pi^- \rightarrow \mu^-$
$\nu \rightarrow e^-$

10$^{15}$ m$^{-2}$ s$^{-1}$
2 - 3 ion pairs cm$^{-3}$ s$^{-1}$

Hard component (50-80%)
Soft component ($\sim 10\%$)

Van Allen belts

Nuclear reactions producing
$^3$H, 2500 m$^{-2}$ s$^{-1}$
$^{10}$Be, 300 m$^{-2}$ s$^{-1}$
$^{14}$C, 22000 m$^{-2}$ s$^{-1}$

Radioactivity from minerals
$^{40}$K, $^{232}$Th, $^{238}$U, etc

Very little absorption
Electromagnetic Radiation

Initially from the sun, other stars, galaxies, and the Big Bang. This radiation spans the whole electromagnetic energy spectrum from high energy gamma radiation to low energy long-wave radiation.

It is estimated that the Universe in average contains about 400 photons/cm$^3$. We are also surrounded by a "sea" of photons with wave-lengths from 0.1 mm to 10 cm arriving with almost the same intensity from all directions. This radiation corresponds to black-body radiation at 2.7 K and is assumed to remain from the Big Bang, and doppler-shifted to this low energy when space expands.

Radiation from the sun is equivalent to black-body radiation at 6000 K. At the surface of the Earth, the spectrum is modified by absorption in our atmosphere.
Gamma Ray Bursts

- Short (1-100 ms) pulses of intense $\gamma$-radiation
- Sources: most probably neutron stars which are ripped apart by nearby black holes.
- Emitted radiation seems to cover a space angle of about 3% in each of two opposite directions.
- Usually these events are observed in other nearby galaxies and the rapidly fading afterglow from the source in visible light has often been observed.
- In case such an outburst should occur in our galaxy and the radiation hit us, it would be a complete disaster for our atmosphere. The risk is real, but its size is uncertain.
A Gamma Ray Burst
As pictured by an artist
Even the Earth emits x-rays and hard $\gamma$-rays to space in short bursts. Discovered by x-ray and $\gamma$-ray-burst recording satellites. The mechanism is unknown, but large thunderstorms are suspected to be a possible source (lightning strikes?).

Some $\gamma$-rays of high energy are also believed to be accelerated by the shock-wave from supernovas (”ping-pong” Fermi acceleration).

The origin of the majority of high energy $\gamma$-rays is still unknown because earlier theoretical explanations have now been falsified by data from new observations (2009).
A Chandra X-ray image of Tycho's supernova remnant. Evidence had been found here of cosmic ray acceleration. Image: NASA/CXC/Rutgers/J Warren and J Hughes et al.
Particle Radiation

Composition: All mass numbers, but most $^1\text{H}$

Sources: The Sun

  The smaller part, non isotropic (directional), mostly $^1\text{H}$, but also $^3\text{H}$, $E < 10^7$ MeV (causes also the north and south polar lights)

Other nearby stars

Galaxies:

  The major part, isotropic (same from all directions), mostly $^1\text{H}$, no $^3\text{H}$, Energies from $10^7$ to $10^{13}$ MeV

It is believed that particle radiation from galaxies is generated by acceleration in varying magnetic fields and the galaxy’s rotation.
The van Allen Belts around Earth

Cross section of the Earth's magnetosphere and the Van Allen belts, as revealed by numerous spacecraft.
The magnetic bubble around the Earth
Northern Lights (Aurora)

In space, outside our atmosphere, and in the magnetosphere there is a plasma of fast charged particles. During so called magnetic storms it is possible for these particles to descend into the atmosphere. The particles react with, excites, the atoms they encounter. When the excited atoms de-excite light is emitted. The yellow-green color often seen originates from de-excitation of atomic oxygen.
Aurora in Canada
Aurora on Earth seen from space
Aurora on Saturn
At present the sun's magnetic field and the solar wind is increasing from a minimum. More new solar spots are seen. The increasing magnetic field forces many particles from outside the solar system to deviate. This affects the occurrence of polar lights and also to some extent the cosmic radiation level at the surface.
Annual (blue) and running 11 yr average (red) sunspot number; SIdC
Voyager space craft

Powered by the heat from Pu-238 since the 1977
Current positions outside solar system

Artist drawing from NASA 2013
Deflection of cosmic ray particles