High Altitude Water Cherenkov
Gamma-Ray Observatory

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10th Winter School on Astroparticle Physics, 21-29 December, 2015, Bose Institute, Darjeeling, India

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

UNIVERSIDAD DE GUADALAJARA

PARTICLES AND ASTROPARTICLES

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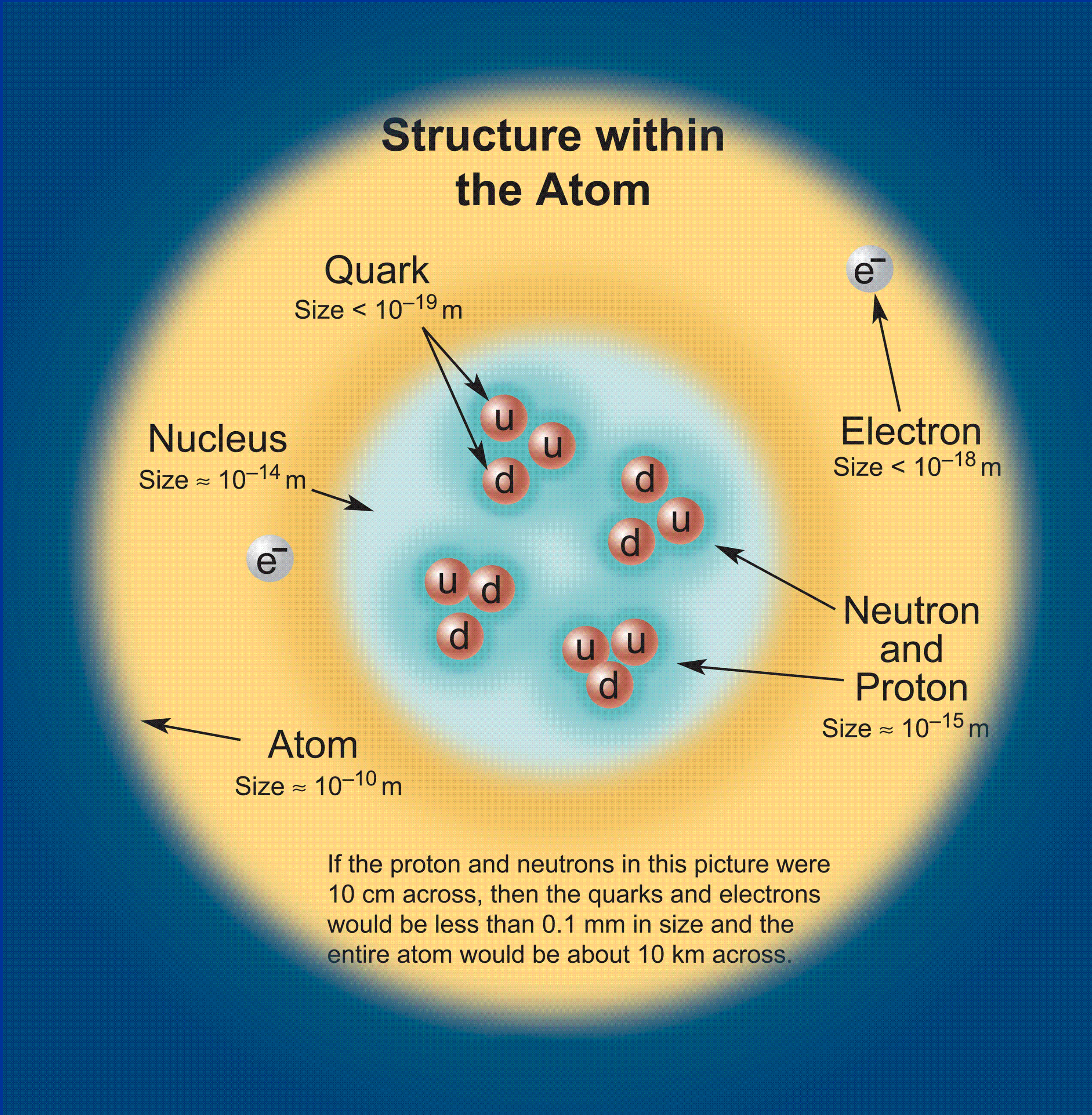
Particle Physics or High Energy Physics

- Is looking for the *smallest constituents of matter* (the "ultimate building blocks") and for the *fundamental forces* between them ("interactions");

- Aim is to find *description in terms of the smallest number of particles and forces*



Definitions:

Fundamental Particle: Particle that cannot be divided, as a lepton or quark (Dictionary definition), with a unique set of properties:

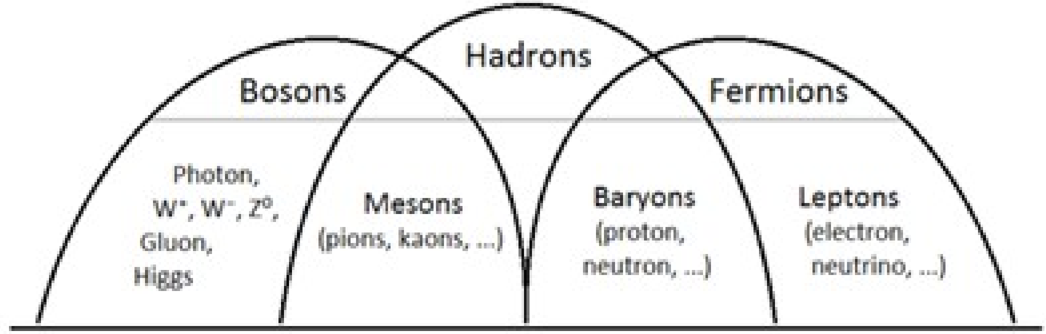
Mass, charge, spin (s = 1/2 integer: Fermion; s = 0,1,2 : Boson), and flavor

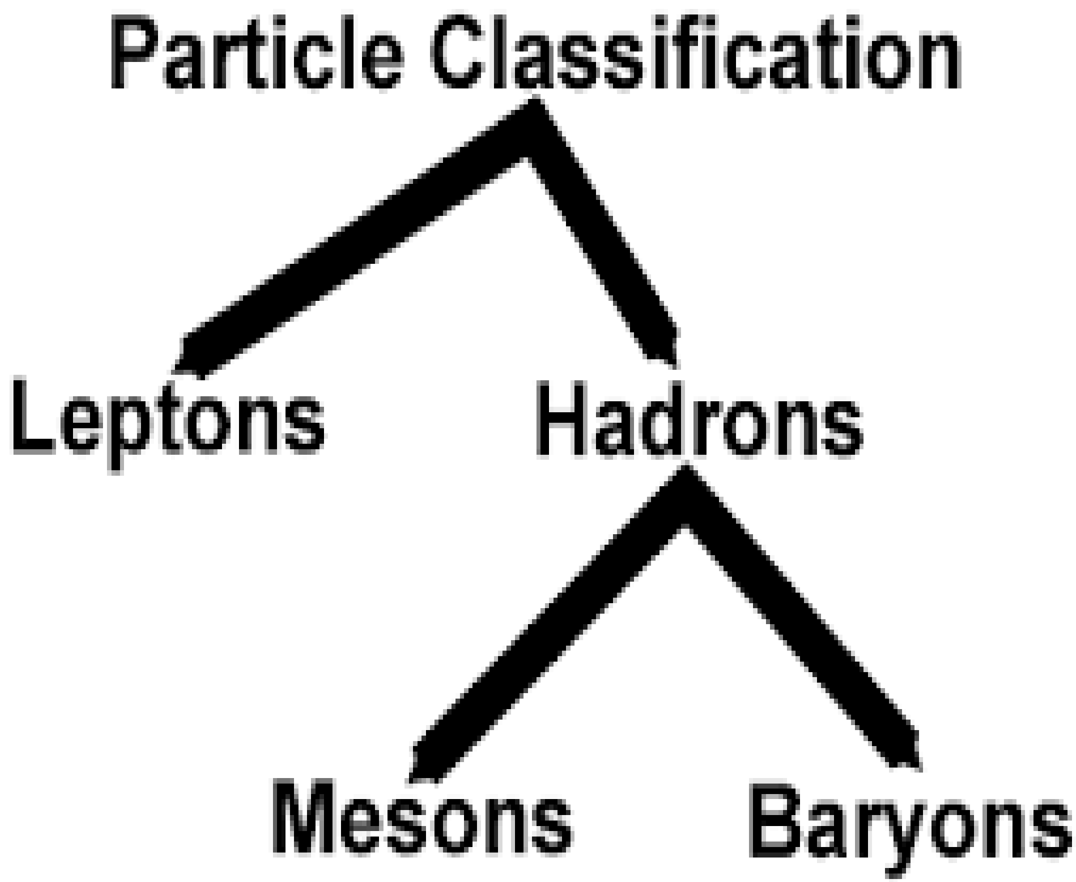
Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

Charge (Q) is a quantity we have defined in order to describe how certain particles (with this charge) interact. If the particles don't interact in the prescribed way, they don't have charge.


Hadrons
Bosons
Fermions
Photon, W^+, W^-, Z^0, Gluon, Higgs
Mesons (pions, kaons, ...)
Baryons (proton, neutron, ...)
Leptons (electron, neutrino, ...)


Particle Classification
Leptons
Hadrons
Mesons
Baryons

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

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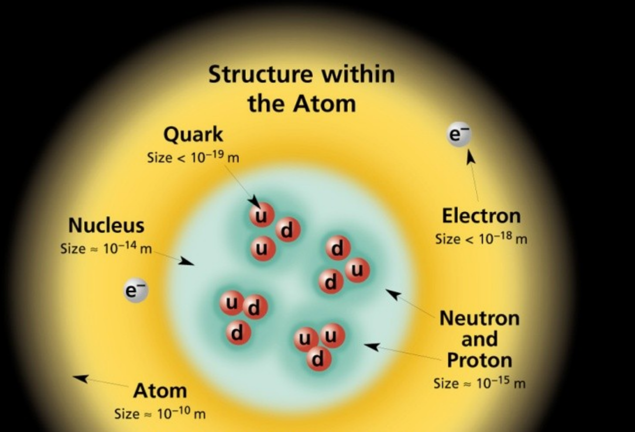


If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

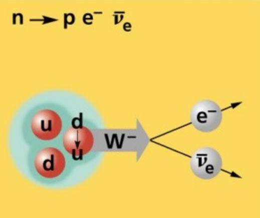
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

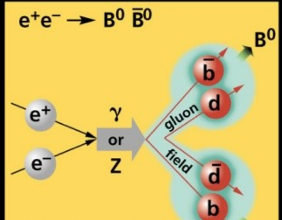
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

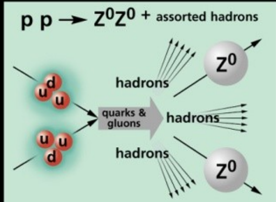
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

This chart has been made possible by the generous support of:
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Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction (Electroweak)	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Fundamental Particles:

FERMIONS

matter constituents
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Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Leptons: Neutrinos spin = - 1 / 2

HADRONS: Composed by Quarks and joined by the strong force (Barions and Mesons.

MESONS

* Masses are between those of leptons & baryons.

* They are unstable.

* They decay into lighter mesons or leptons.

* They have either positive, negative at zero charge.

* The mesons include the pion, kaon and eta particles.

Mesons $q\bar{q}$

Mesons are bosonic hadrons

These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
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η_c	eta-c	$c\bar{c}$	0	2.980	0

From Contemporary Physics Education Project
http://www.cpepweb.org/particles.html

BARYONS (Or) heavy particles

* Protons & particles heavier than proton form this group.

* Proton and neutron are called nucleons and the rest mass are called hyperons.

* Every baryons has an antiparticle.

* If a number, called the baryon number +1 is assigned to baryons and a number -1 is assigned to antibaryons, then in any closed system interaction or decay, the baryon number does not change. This is the law of conservation of baryons.

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
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n	neutron	**udd**	0	0.940	1/2
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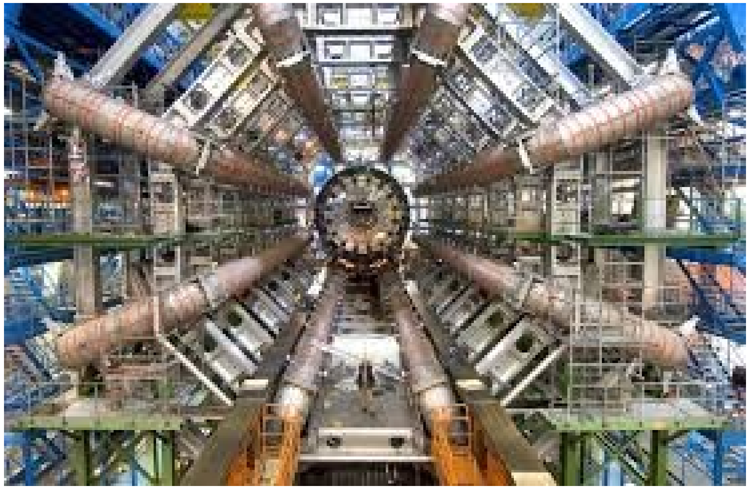
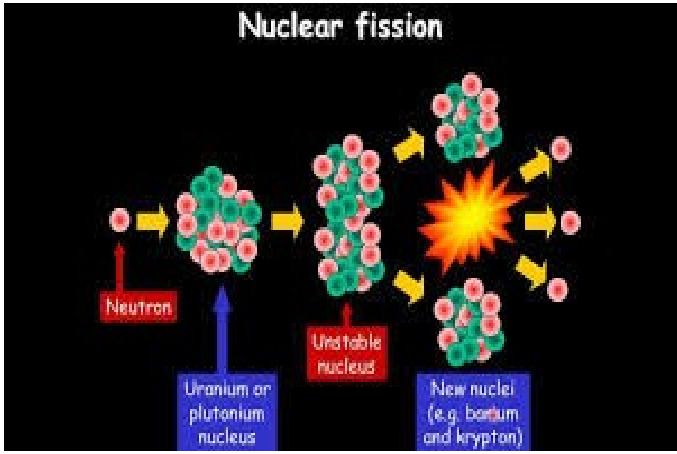
Particle Physics and High Energy Physics

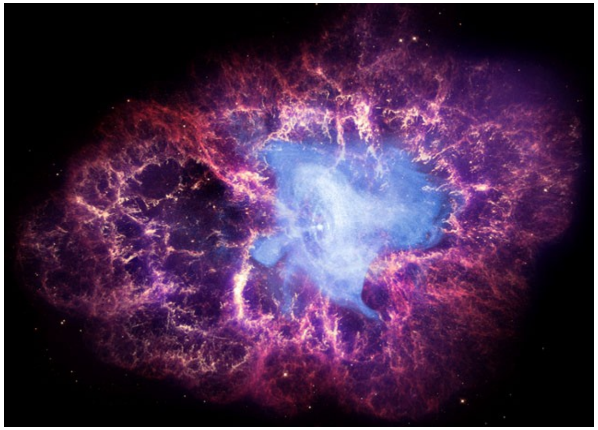
- Particle Physics can be divided on 3 areas:



2.- NUCLEAR PHYSICS



1.- ACCELERATOR PHYSICS



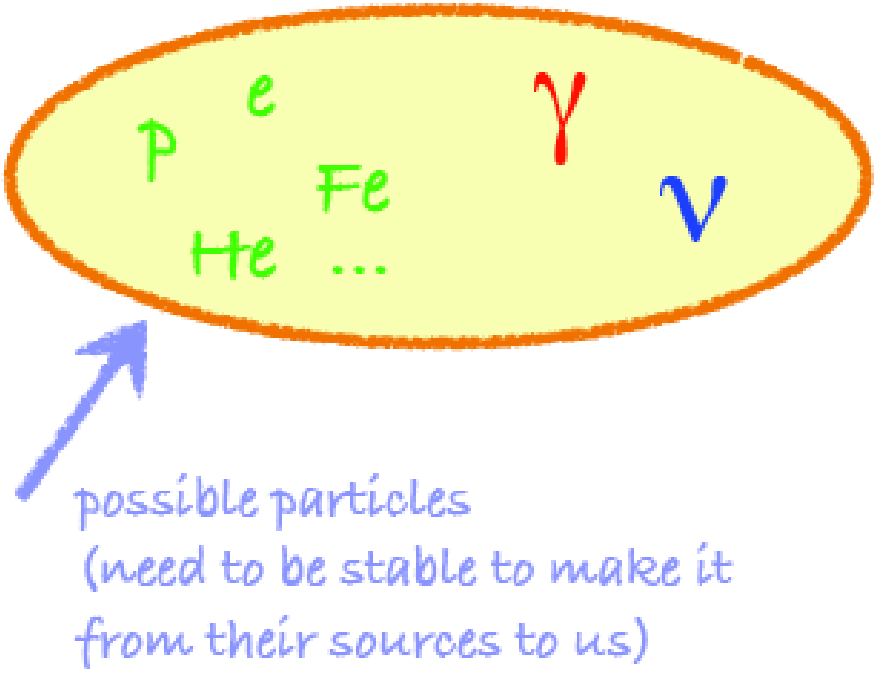
3.- ASTROPARTICLES

High Energy Astrophysics: Energy from few MeVs to PeVs (X-Ray to CR)

Astroparticles: (definition today)

Particles from astrophysical sources

... the highest energy particles in the universe !!!!!



Slide from Prof. Johannes Knapp Lectures WAPP 2012 (see it on webpages)

If	Cosmic Rays exist,
then	also ν and γ must exist
	at similar energies.

But: can they be detected above backgrounds ???

γ : 100-1000 x more cosmic rays

ν : low interaction cross section

atmospheric neutrinos from atmosphere

Slide from Prof. Johannes Knapp Lectures WAPP 2012 (see it on webpages)

Cosmic Rays, Gamma Rays and Neutrinos are linked

$$\text{p, He, ... Fe} \longrightarrow \pi^{\pm}, \ \pi^{0}$$

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}$$

$$\mu^{\pm} \longrightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

$$\pi^{0} \longrightarrow \gamma\gamma$$

$$e^{-} \longrightarrow \gamma$$

only charged particles can be accelerated by el.mag. fields

very difficult to detect

can't travel far at high energies

γ and ν travel in straight lines, i.e. point back at source. CRs are deflected in galactic and intergalactic magnetic fields.

Slide from Prof. Johannes Knapp Lectures WAPP 2012 (see it on webpages)

Extreme Energies ....

.... Extreme Environments:

Power sources ?

Accretion of matter onto compact objects

e.g. Neutron stars, black holes, supermassive black holes

Explosions: Supernova (SN), compact binary mergers

Rotation: rotating neutron star with strong magnetic field

generate relativistic electron-positron wind

How ? (all on charged particles)

Diffusive shock (Fermi) acceleration e.g. SN blast wave hits ISM

Magnetic reconnection ? Plasma waves ?

Creation of gamma rays ?

π^0 decay — hadronic primaries

synchrotron emission in magnetic fields
Inverse Compton effect — relativistic e^+, e^-

Slide from Prof. Johannes Knapp Lectures WAPP 2012 (see it on webpages)

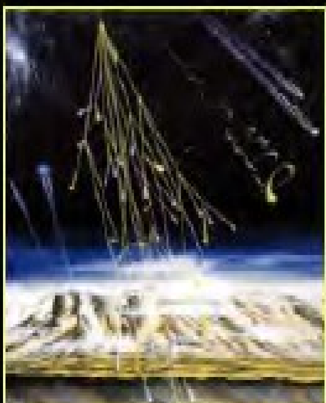
Astrophysical Questions:

Origin :	Where are they from?
	How do their sources work?
Identity :	What are they?
Acceleration :	How do they get their energy?
Propagation :	What happens on their way?

by measuring their:

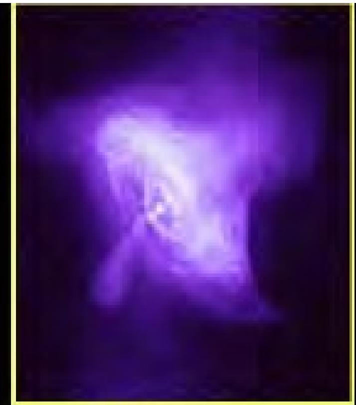
Energy spectrum
Composition
Arrival directions

See Prof. Johannes Knapp Lectures WAPP

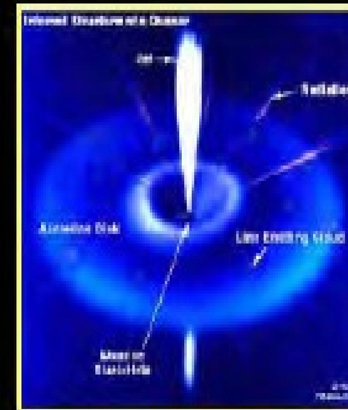


Origin of cosmic rays

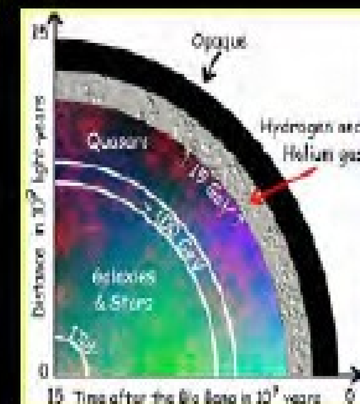
SNRs



Pulsars and PWN

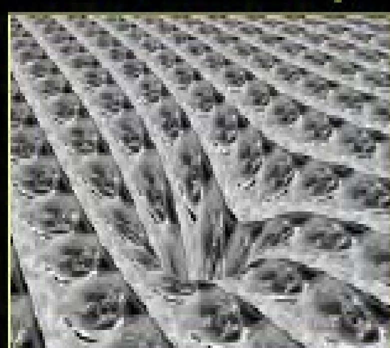


AGNs



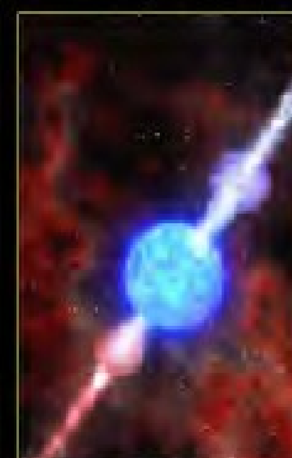
Cosmology

Space-time & relativity



Dark matter

GRBs



MESONS

Particle	Symbol	Anti-particle	Makeup	Rest mass MeV/c^2	S	C	B	Lifetime	Decay Modes
Pion	π^+	π^-	**$u\underline{d}$**	**139.6**	**0**	**0**	**0**	**2.60 $\times 10^{-8}$**	$\mu^+\nu_\mu$
Pion	π^0	**Self**		**135.0**	**0**	**0**	**0**	**0.83 $\times 10^{-16}$**	**2γ**
Kaon	$\mathbf{K^+}$	$\mathbf{K^-}$	$u\underline{s}$	493.7	+1	0	0	1.24 $\times 10^{-8}$	$\mu^+\nu_\mu$, $\pi^+\pi^0$
Kaon	$\mathbf{K^0_s}$	$\mathbf{K^0_s}$	1*	497.7	+1	0	0	0.89 $\times 10^{-10}$	$\pi^+\pi^-$,$2\pi^0$
Kaon	$\mathbf{K^0_L}$	$\mathbf{K^0_L}$	1*	497.7	+1	0	0	5.2 $\times 10^{-8}$	$\pi^+ e^- \underline{\nu}_e$
Eta	η^0	Self	2*	548.8	0	0	0	$<10^{-18}$	2γ, 3μ
Eta prime	$\eta^{0'}$	Self	2*	958	0	0	0	…	$\pi^+\pi^-\eta$
Rho	ρ^+	ρ^-	$u\underline{d}$	770	0	0	0	0.4 $\times 10^{-23}$	$\pi^+\pi^0$
Rho	ρ^0	Self	$u\underline{u}$, $d\underline{d}$	770	0	0	0	0.4 $\times 10^{-23}$	$\pi^+\pi^-$
Omega	ω^0	Self	$u\underline{u}$, $d\underline{d}$	782	0	0	0	0.8 $\times 10^{-22}$	$\pi^+\pi^-\pi^0$
Phi	φ	Self	$s\underline{s}$	1020	0	0	0	20 $\times 10^{-23}$	K^+K^-,$K^0\underline{K}^0$
D	$\mathbf{D^+}$	$\mathbf{D^-}$	$c\underline{d}$	1869.4	0	+1	0	10.6 $\times 10^{-13}$	K + _, e + _
D	$\mathbf{D^0}$	$\underline{\mathbf{D}}^0$	$c\underline{u}$	1864.6	0	+1	0	4.2 $\times 10^{-13}$	[K,μ,e] + _
D	$\mathbf{D^+_s}$	$\mathbf{D^-_s}$	$c\underline{s}$	1969	+1	+1	0	4.7 $\times 10^{-13}$	K + _

BARIONS

Particle	Symbol	Makeup	Rest mass MeV/c^2	Spin	B	S	Lifetime (second s>	Decay Modes
Proton **PROTON**	**p**	**uud**	**938.3**	**1/2**	**+1**	**0**	**Stable**	...
Neutron	n	ddu	939.6	1/2	+1	0	920	$pe^-\bar{\nu}_e$
Lambda	Λ^0	uds	1115.6	1/2	+1	-1	2.6×10^{-10}	$p\pi^-$, $n\pi^0$
Sigma	Σ^+	uus	1189.4	1/2	+1	-1	0.8×10^{-10}	$p\pi^0$, $n\pi^+$
Sigma	Σ^0	uds	1192.5	1/2	+1	-1	6×10^{-20}	$\Lambda^0\gamma$
Sigma	Σ^-	dds	1197.3	1/2	+1	-1	1.5×10^{-10}	$n\pi^-$
Delta	Δ^{++}	uuu	1232	3/2	+1	0	0.6×10^{-23}	$p\pi^+$
Delta	Δ^+	uud	1232	3/2	+1	0	0.6×10^{-23}	$p\pi^0$
Delta	Δ^0	udd	1232	3/2	+1	0	0.6×10^{-23}	$n\pi^0$
Delta	Δ^-	ddd	1232	3/2	+1	0	0.6×10^{-23}	$n\pi^-$
Xi Cascade	Ξ^0	uss	1315	1/2	+1	-2	2.9×10^{-10}	$\Lambda^0\pi^0$
Xi Cascade	Ξ^-	dss	1321	1/2	+1	-2	1.64×10^{-10}	$\Lambda^0\pi^-$
Omega minus	Ω^-	sss	1672	3/2	+1	-3	0.82×10^{-10}	$\Xi^0\pi^-$, Λ^0K^-

Properties of the Leptons

Particle	Symbol	Anti-particle	Rest mass MeV/c^2	L(e)	L(muon)	L(tau)	Lifetime (seconds)
Electron	e^-	e^+	0.511	+1	0	0	Stable
Neutrino (Electron)	ν_e	$\underline{\nu}_e$	0(<7 x 10^{-6})	+1	0	0	Stable
Muon	μ^-	μ^+	105.7	0	+1	0	2.20x10^{-6}
Neutrino (Muon)	ν_μ	$\underline{\nu}_\mu$	0(<0.27)	0	+1	0	Stable
Tau	τ^-	τ^+	1777	0	0	+1	2.96x10^{-13}
Neutrino (Tau)	ν_τ	$\underline{\nu}_\tau$	0(<31)	0	0	+1	Stable

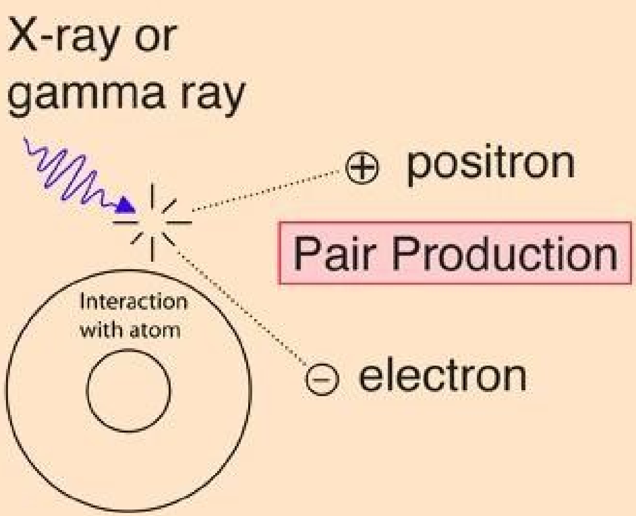
Numerical data from Giancoli

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Electron-Positron Pair Production

When a photon has quantum energy higher than the rest mass energy of an electron plus a positron, one of the ways that such a photon interacts with matter is by producing and electron-positron pair.



The rest mass energy of the electron is 0.511 MeV, so for photon energy above 1.022MeV, pair production is possible. For photon energies far above this threshold, pair production becomes the dominant mode for the interaction of x-rays and gamma-rays with matter.

See Hyperphysics webpage

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

UNIVERSIDAD DE GUADALAJARA

THEORY OF THE CHERENKOV RADIATION

10th Winter School on Astroparticle Physics, 21-29 December, 2015, Bose Institute, Darjeeling, India

Maxwell's Equations (SI Units)

Coulomb's law:	$\nabla \bullet \mathbf{E} = \rho / \varepsilon o$
Gauss's law:	$\nabla \bullet \mathbf{B} = 0$
Faraday's law	$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$
Ampere's law: (with Maxwell's addition)	$\nabla \times \mathbf{B} = \mu o\, J + \mu o\, \varepsilon o\, (\partial \mathbf{E}/\partial t)$

Where **E** is the electric field (a **vector**: 3 components)
B is the magnetic field (**vector**)
ρ is the electrical charge density (a scalar: no direction)
εo is the permittivity of free space ($\sim 8.85 \times 10^{-12}$ F/m)
μo is the permeability of free space ($4\pi \times 10^{-7}$ H/m)
$\mu o\, \varepsilon o = 1 / c^2$ (the square of the speed of light)
∇ is the "Del" operator (a gradient or change in space)
$\nabla \bullet$ is the "Divergence" operator (results in a scalar)
$\nabla \times$ is the "Curl" operator (results in a **vector**)
$\partial \mathbf{B}/\partial t$ is the time rate of change of the magnetic field (**vector**)
$\partial \mathbf{E}/\partial t$ is the time rate of change of the electric field (**vector**)

Courtesy J. C. Maxwell, 1861 "On Physical Lines of Force"
Printout courtesy **NASA MMS** http://MMS.rice.edu

Taking the divergence of both sides of Ampere's law and using Gauss's law

$$\nabla \cdot \nabla \times H = \nabla \cdot J + \nabla \cdot \frac{\partial D}{\partial t} = \nabla \cdot J + \frac{\partial}{\partial t}\nabla \cdot D = \nabla \cdot J + \frac{\partial \rho}{\partial t}$$

$$\boxed{\frac{\partial \rho}{\partial t} + \nabla \cdot J = 0} \qquad \text{(charge conservation)}$$

$$\begin{aligned} \vec{\nabla} \cdot \vec{E} &= 0 \\ \vec{\nabla} \cdot \vec{B} &= 0 \\ \vec{\nabla} \times \vec{E} &= -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \\ \vec{\nabla} \times \vec{B} &= \frac{1}{c}\frac{\partial \vec{E}}{\partial t} \,. \end{aligned}$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{E} = \vec{\nabla}\left(\vec{\nabla} \cdot E\right) - \nabla^2 \vec{E} = -\nabla^2 \vec{E} \,.$$

$$\frac{\partial^2 \vec{E}}{\partial t^2} - c^2 \frac{\partial^2 \vec{E}}{\partial x^2} = 0$$

$$c = \frac{1}{\sqrt{\mu\epsilon}}$$

What happens If a drop a pebble into a pound

What happens If dropping pebbles at regular time

What happens If move my hand (no concentric)

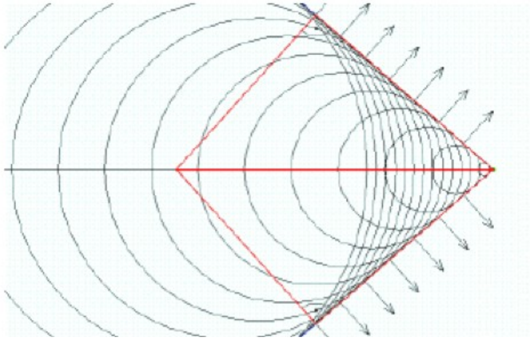
What happens If I move my hand at the same speed that the rings move (all the rings will touch in a point)

What happens if I move the source of the ripples faster that the speed of the ripples can spread?

The duck is travel faster than the speed of the ripples it creates. Individual waves can not spread in front of the duck

The object creating waves is travel faster that the speed of the wave itself

The duck is swimming on the surface of the water faster than the speed wave travel over the surface.



Cherenkov Radiation

- Particle speed must be larger than the phase speed of light in the medium:

$$\beta > \frac{1}{n};$$

- Radiation with shorter wavelength are more intense:

$$\frac{d^2\mathcal{E}_\omega}{d\omega dz} \propto \omega;$$

- The emission angle of Cherenkov radiation with fixed frequency is also fixed:

$$\theta = \arccos(1/n(\omega)\beta).$$

- Frank-Tamm Theory (1937; Nobel in 1958):

$$\frac{dW}{dl} = \frac{e^2}{c^2}\int_{\beta n>1}\left(1-\frac{1}{\beta^2 n^2}\right)\omega d\omega$$

Cherenkov Emission

- Cherenkov effect occurs when the velocity of a charged particle traversing a dielectric medium exceeds the velocity of light in that medium ($v>c/n$)

- Excited atoms in the vicinity of the particle trajectory become polarized and coherently emit radiation

- A small number of photons are emitted at a fixed angle, which is determined by the velocity of the particle and the index of refraction of the medium => **$\cos\theta = 1/n\beta$**

- The index of refraction of the medium, n, is a function of wavelength (λ) and temperature. The general tendency for n is to decrease with increasing λ. The variation $dn/d\lambda$ (referred to as dispersion), is largest in the ultraviolet portion of the spectrum.

- Cherenkov light is emitted almost instantly. The angular distribution of the light intensity is approx. a δ function at the Cherenkov angle θ. The actual distribution is broadened due to dispersion, energy loss of the particle, multiple scattering & diffraction.

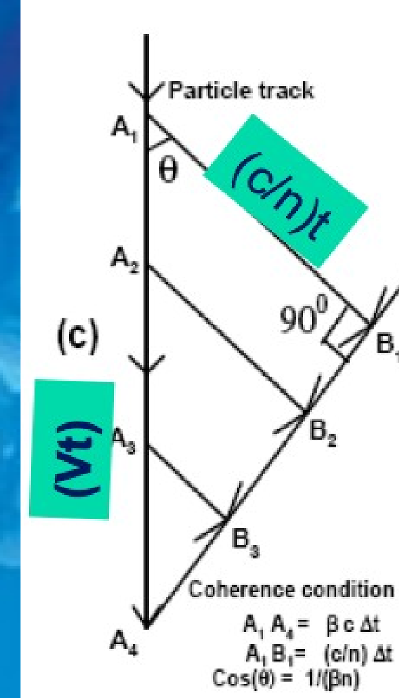
THIS IS SLIDE 26 OF B.S. Acharya TALK (WAPP 2012)

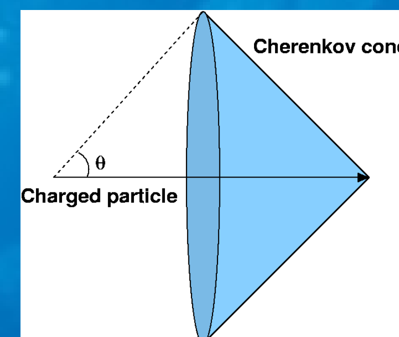
- .The charged particle polarizes the atoms along its trajectory

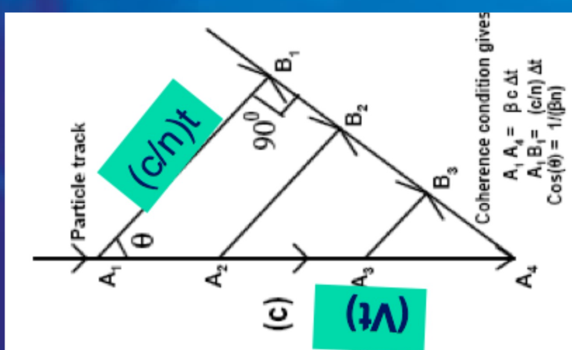
- These time dependent dipole emit electromagnetic radiation

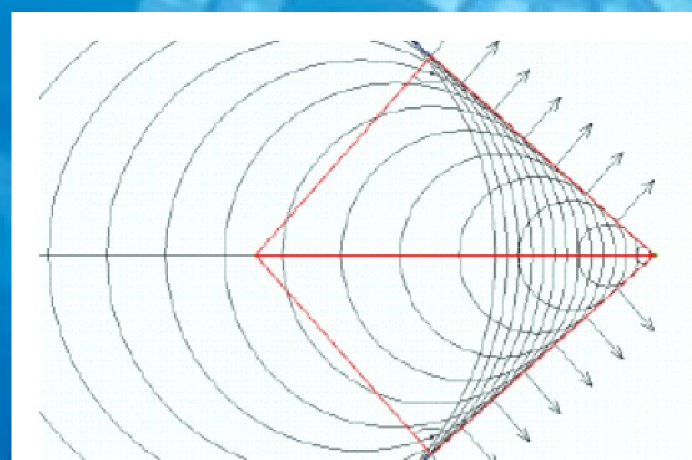
- If v < c / n, the dipole distribution is symmetric around the particle position, and the sum of all dipoles vanishes

- If v > c / n, the distribution is asymmetric and the total time dependent dipole is not null, thus radiates.







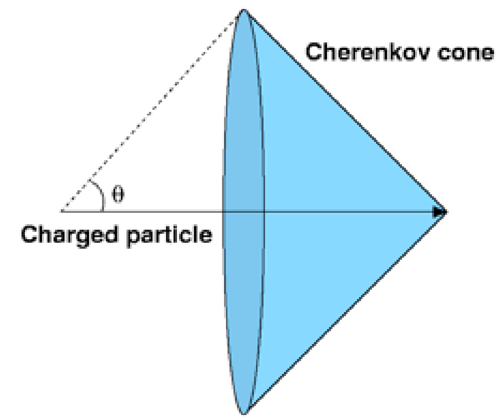


See also slide 22 of B.S. Acharya talk and shock wave discussion by Dr. Chernyshov (WAPP 2012 website)

Čerenkov radiation

From a medium of refraction index n traversed by a charged particle with $v > c/n$.

Radiation follow the particle inside a cone of aperture $cos(\theta)=1/n\beta$.



Medium	n	Threshold (γ)	θ_{max} (º)	dE/dx (eV/cm)
Air	1.0003	40.8	1.4	0.34
Water	1.335	1.5	41.2	3.27

PROBLEM

1) Derive in detail the expresion that describes the Cerenkov radiation.

Idem and discuss about the shape of the front wave.

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \tag{1a}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} + \frac{4\pi}{c}\mathbf{j}, \tag{1b}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{1c}$$

$$\nabla \cdot \mathbf{D} = 4\pi\varrho, \tag{1d}$$

$$\mathbf{D} = \hat{\epsilon}\mathbf{E},$$

where $\hat{\epsilon}$ is the permittivity operator $\hat{\epsilon}\exp(-i\omega t) = \epsilon(\omega)\exp(-i\omega t)$, and $\epsilon(\omega)$ is the permittivity of the medium.

Introducing the potentials $\mathbf{A}$ and ϕ,

$$\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} - \nabla\phi, \tag{2a}$$

$$\mathbf{B} = \nabla \times \mathbf{A}, \tag{2b}$$

and imposing the generalized Lorentz condition on the potentials,

$$\nabla \cdot \mathbf{A} + \frac{\hat{\epsilon}}{c}\frac{\partial \phi}{\partial t} = 0, \tag{3}$$

the macroscopic Maxwell equations (1) can be written as

$$\nabla^2 \mathbf{A} - \frac{\hat{\epsilon}}{c^2}\frac{\partial^2}{\partial t^2}\mathbf{A} = -\frac{4\pi}{c}\mathbf{j}, \tag{4a}$$

$$\hat{\epsilon}\left(\nabla^2\phi - \frac{\hat{\epsilon}}{c^2}\frac{\partial^2}{\partial t^2}\phi\right) = -4\pi\varrho, \tag{4b}$$

What A, Phi, and the generalized Lorentz condition physically means. Give Expresions and discuss

Cherenkov radiation can be described just with the equation for the vector potential,

$$\nabla^2 \mathbf{A} - \frac{\hat{\epsilon}}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} = -\frac{4\pi}{c}\mathbf{j}. \tag{5}$$

We first expand **A** and **j** as a Fourier time integral,

$$\mathbf{A}(\mathbf{r}, t) = \int_{-\infty}^{\infty} \mathbf{A}_\omega(\mathbf{r}) e^{-i\omega t} \frac{d\omega}{2\pi}. \tag{6}$$

$$\mathbf{j}(\mathbf{r}, t) = \int_{-\infty}^{\infty} \mathbf{j}_\omega(\mathbf{r}) e^{-i\omega t} \frac{d\omega}{2\pi} \tag{7}$$

After Fourier transformation, Eq. (5) becomes

$$\nabla^2 \mathbf{A}_\omega(\mathbf{r}) + \frac{\epsilon\omega^2}{c^2}\mathbf{A}_\omega(\mathbf{r}) = -\frac{4\pi}{c}\mathbf{j}_\omega(\mathbf{r}). \tag{8}$$

What a vector potential physically means. Give Expresions and discuss. Do all steps, avoid " It is clear, Obvious, etc...". Do the Fourier transformation and the expansion in detail.

Eq. (8) has the form of the inhomogeneous Helmholtz equation, and has a solution as follows,

$$\mathbf{A}_\omega(\mathbf{r}) = \frac{1}{c}\int \frac{\mathbf{j}_\omega(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\exp[i\omega|\mathbf{r}-\mathbf{r}'|\sqrt{\epsilon}/c)]d^3r', \tag{9}$$

The radiation field should be just proportional to $1/r$ at the distance far from the radiator. When $r \gg r'$, we approximately have $|\mathbf{r}-\mathbf{r}'| \approx r - \mathbf{n}\cdot\mathbf{r}'$, where $\mathbf{n} = \mathbf{r}/r$. The vector potential corresponding to radiation can be approximately written as

$$\mathbf{A}_\omega(\mathbf{r}) = \frac{\exp(ikr)}{cr}\int \mathbf{j}_\omega(\mathbf{r}')\exp(-i\mathbf{k}\cdot\mathbf{r}')d^3r', \tag{10}$$

where $\mathbf{k} = n(\omega/c)\mathbf{n}$, and $n = \epsilon^{1/2}$ is the refractive index of the medium.

What the inhomogeneous Helmholtz equation physically means. Give Expresions and discuss. All steps, avoid “ It is clear, Obvious, etc…”. Do the aproximation in detail.

For an electron, the current can be written as

$$\mathbf{j}(t, \mathbf{r}) = -e\mathbf{v}(t)\delta[\mathbf{r} - \mathbf{r}_0(t)], \tag{11}$$

where $\delta(x)$ is the $\delta-$function, $\mathbf{r}_0(t)$ is the trajectory of the electron, and e is the electron charge. The Fourier component of the current (11) is given by

$$\mathbf{j}_\omega(\mathbf{r}) = -e\int_{-\infty}^{\infty} \mathbf{v}(t)\delta[\mathbf{r} - \mathbf{r}_0(t)]e^{i\omega t}dt. \tag{12}$$

Substituting Eq. (12) into Eq. (10), and integrating over the volume d^3r', we obtain

$$\mathbf{A}_\omega = -\frac{e}{cr}e^{ikr}\int_{-\infty}^{\infty} \mathbf{v}(t)\exp[i\omega t - i\mathbf{k}\cdot\mathbf{r}_0(t)]dt.$$

Do the last step in detail, and derive (12)

The magnetic field of the radiation is then given by

$$\mathbf{B}_\omega = \nabla \times \mathbf{A}_\omega \approx -\frac{iek}{cr} e^{ikr} \int_{-\infty}^{\infty} \mathbf{n} \times \mathbf{v}(t) e^{i[\omega t - \mathbf{k}\cdot\mathbf{r}_0(t)]} dt. \tag{13}$$

Here we just keep the term proportional to $1/r$.
From the equation of $\nabla \times \mathbf{E} = -(1/c)(\partial \mathbf{B}/\partial t)$, the electric field of the radiation is also obtained,

$$\mathbf{E}_\omega = \frac{\omega}{kc} \mathbf{B}_\omega \times \mathbf{n} = \frac{1}{n} \mathbf{B}_\omega \times \mathbf{n}. \tag{14}$$

The radiation energy through the section $\mathbf{n}R^2 d\Omega$ at the distance far from the charge is given by

$$d\mathcal{E} = \frac{c}{4\pi} \left[\int_{-\infty}^{\infty} (\mathbf{E} \times \mathbf{B}) \cdot \mathbf{n} dt \right] R^2 d\Omega = \frac{c}{4\pi^2} \left[\int_0^\infty \frac{1}{n} |\mathbf{B}_\omega|^2 d\omega \right] R^2 d\Omega. \tag{15}$$

Why equation (15). Explain and derive in detail.

Substituting Eqs. (13) and (14) into Eq. (15), we obtain the spectral intensity of the radiation,

$$\frac{d^2\mathcal{E}_{\omega\mathbf{n}}}{d\omega d\Omega} = \frac{e^2\omega^2 n}{4\pi^2 c^3}\left|\int_{-\infty}^{\infty}\mathbf{n}\times\mathbf{v}(t)e^{i[\omega t-\mathbf{k}\cdot\mathbf{r}_0(t)]}dt\right|^2. \tag{16}$$

In the case that an electron moves uniformly along $z-$axis, i.e., $\mathbf{v} = v\mathbf{e}_z$ and $\mathbf{r}_0 = vt\mathbf{e}_z$, using the formula

$$\delta(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{i\omega t}dt,$$

we have

$$\frac{d^2\mathcal{E}_{\omega\mathbf{n}}}{d\omega d\Omega} = \frac{e^2\omega^2 n}{2\pi c^3}v\sin^2\theta\delta(\omega-\mathbf{k}\cdot\mathbf{v})\int_{-\infty}^{\infty}dz. \tag{17}$$

What the delta(omega) function is, means?. Derive (16) and (17) in detail.

Integrating Eq. (19) over the solid angle $d\Omega$, we obtain

$$\frac{d^2\mathcal{E}_\omega}{d\omega dz} = \begin{cases} \frac{e^2\omega}{c^2}\left(1 - \frac{1}{n^2\beta^2}\right), \text{ when } \frac{1}{n\beta} < 1, \\ 0, \text{ when } \frac{1}{n\beta} > 1. \end{cases} \tag{18}$$

Cherenkov radiation is emitted only when the following condition is satisfied,

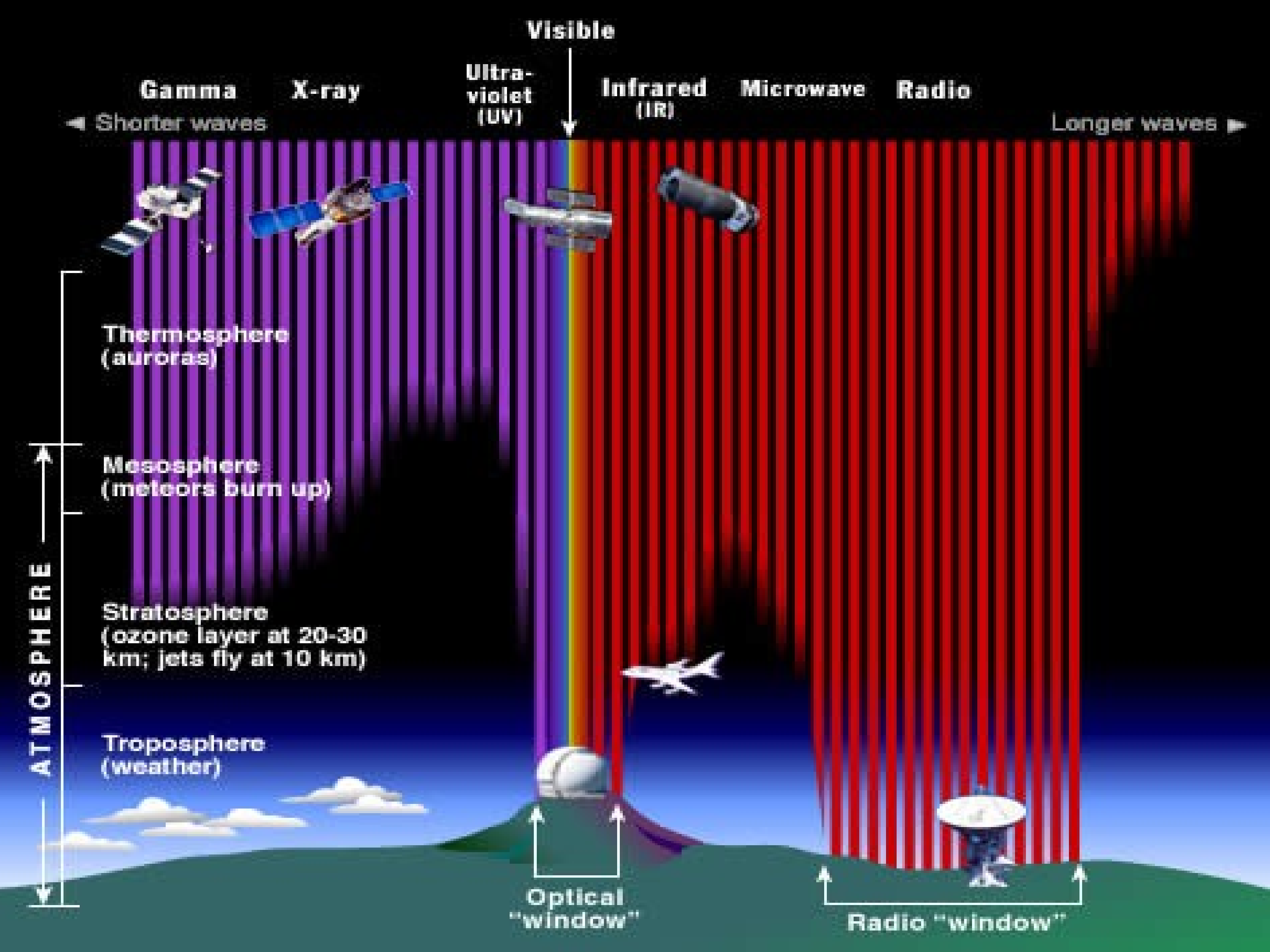
$$\frac{1}{n\beta} < 1. \tag{19}$$

The photon yield of Cherenkov radiation within the wavelength interval from $\lambda \to \lambda + d\lambda$ is given by

$$dN_\lambda = 2\pi\alpha\left(1 - \frac{1}{n^2\beta^2}\right)\frac{d\lambda}{\lambda}\frac{dz}{\lambda}, \tag{20}$$

where $\alpha = e^2/\hbar c = 1/137$ is the fine structure constant.

Discuss about the fine structure constant. Do all steps in detail. No obvious. No skip steps


Visible
Gamma
X-ray
Ultra-violet (UV)
Infrared (IR)
Microwave
Radio
◄ Shorter waves
Longer waves ►
Thermosphere (auroras)
Mesosphere (meteors burn up)
Stratosphere (ozone layer at 20-30 km; jets fly at 10 km)
Troposphere (weather)
ATMOSPHERE
Optical "window"
Radio "window"

I strongly suggest check and understand this talk:

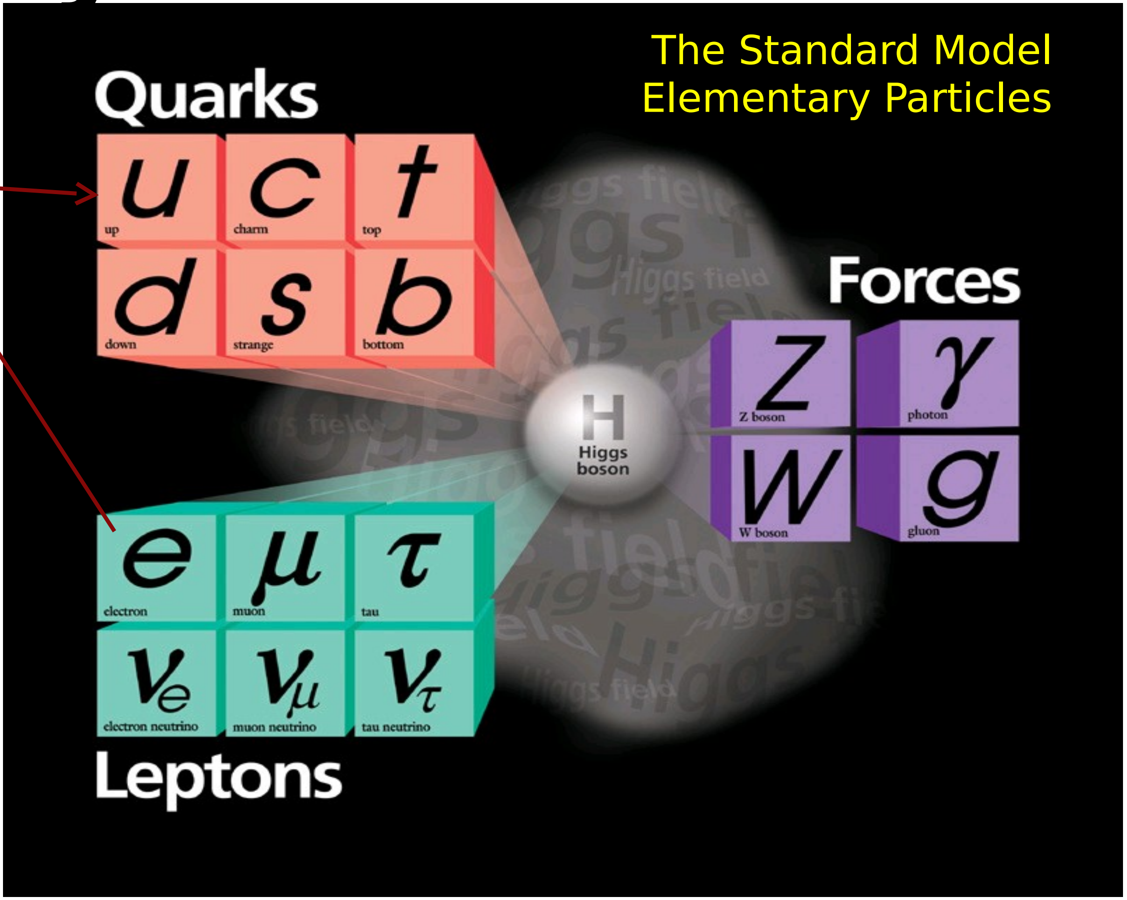
Catch The Elusive Neutrino

Subhasis Chattopadhyay

Variable Energy Cyclotron Centre
&
Bose Institute
Kolkata

Standard Model of Particle Physics

- <u>12 matter particles</u>
  - 6 quarks
  - 6 leptons
  - these 12 building blocks make up all the varieties of “normal” matter in the Universe
- <u>4 forces</u>
  - gravitational force
  - electromagnetic force
  - strong nuclear force
  - weak nuclear force
  - these 4 ways for particles to interact with each other are the only ones we currently know about



Slide from Subhasis Chattopadhyay's Neutrino Talk (WAPP 2015)

High Altitude Water Cherenkov
Gamma-Ray Observatory

THANKS
edfuente@gmail.com

https://www.youtube.com/watch?v=R95h8sqm_Hw

https://www.youtube.com/watch?v=Gt4Y7i-h-h4