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lecture cource on

Astroparticle physics

15.09.2009 – 15.12.2009

A. General things

The lecture cource

- 6 credit units,
  suitable for advanced studies and Ph.D. studies
- Lectures 39 h ($= 13 \times 3$h) every tuesday at 14 – 17,
  first 15.09. and last 15.12.
- Lecturer: Timo Enqvist (timo.enqvist@oulu.fi)
- Excercises 12 h ($= 6 \times 2$h), every second tuesday at 12 – 14,
  starting 06.10.
- Examination methods and dates to be fixed
  - normal way (exam)
  - (comprehensive) literature work
  - data analysis, simulations, ...
- 1/3 of the grade from excercises (60% for full points), and 2/3
  from the examination/literature work/...
- Lecture notes available at http://cupp.oulu.fi/timo

A. General things

Astroparticle physics

- Definition for astroparticle physics (at the present lecture cource)
  - research of particle and nuclear physics without accelerators
  - natural (astronomical) sources and phenomena studied by means of particle and nuclear physics
  - in most cases studied deep underground

B. Lecture Contents

Astroparticle physics: topics and tentative schedule

- high-energy cosmic rays (15.09. and 22.09.) ☞
- past, current and future experiments (06.10.)
- Sun (stars) and solar neutrinos (13.10.)
- supernovae, supernova and relic supernova neutrinos (20.10.)
- atmospheric and geoneutrinos (27.10.)
- double beta-decay (03.11.)
- dark matter (10.11.)
- proton decay (17.11.)
- background in underground measurements (24.11.)
- cosmic microwave background, Big Bang nucleosynthesis (01.12.)
- gravitational waves (08.12.)
- (15.12.)

C. Literature & Articles

Astroparticle physics

- Thomas G. Gaisser: Cosmic Rays and Particle Physics, Cambridge University Press, 1990
- Pierre Sokolsky: Introduction to Ultrahigh Energy Cosmic Rays Physics, Westview Press, 2004
- Claus Grupen: Astroparticle Physics, Springer, 2005
- John N. Bahcall: Neutrino Astrophysics, Cambridge University Press, 1989
- Donald Perkins: Particle Astrophysics, Oxford University Press, 2003
- Claus E. Rolfs and William S. Rodney: Cauldrons in the Cosmos, The University of Chicago Press, 1988
- Donald H. Perkins: Introduction to High Energy Physics, Cambridge University Press, 2000
- Kai Zuber: Neutrino Physics, IOP Publishing Ltd, 2004

0.1 Introduction on particle physics

Particles & interactions

Elementary particles

- Leptons
- Quarks

Interactions

- Strong interaction
- Weak interaction
- Electromagnetic interation
- Gravity

Particle "classes"

- Fermions (particles with half-integer spin, e.g., spin $= 1/2\ \hbar$)
- Bosons (particles with integer spin, e.g., spin $= 1\ \hbar$)
  carriers of all the interactions ☞
  gluons (g), $W^{\pm}$ *and* Z^0 bosons, photons (γ), graviton (G)

0.1 Introduction on particle physics

Terminology

- Leptons – elementary particles not feeling strong interaction (e, μ, ...)
- Hadrons – strongly interacting particles (p, n, π, ...)
  - Baryons – particles with half-interger spin (p, n)
  - Mesons – particles with integer spin (π)
- Fermions – particles with half-interger spin
  - both leptons and hadrons
- Bosons – particles with interger spin
  - mesons
  - gauge bosons (photon, gluon, ...)
  - Higgs boson (not yet found)

0.1 Introduction on particle physics

Leptons

- Leptons are elementary particles
- They belongs to fermions
- They interact via weak and electromagnetic interaction, but neutrinos interact only via weak interaction

Flavour	Symbol	Mass [MeV/c^2]	Lifetime	Q [e]	J	anti-particle
electron	e^-	0.511	stable	-1	1/2	e^+
muon	μ^-	105.7	2.2 μs	-1	1/2	μ^+
tau	τ^-	1777	290 fs	-1	1/2	τ^+
electron-ν	ν_e	$<2.5\times10^{-6}$	stable	0	1/2	$\bar{\nu}_e$
muon-ν	ν_μ	<0.19	stable	0	1/2	$\bar{\nu}_\mu$
tau-ν	ν_τ	<18	stable	0	1/2	$\bar{\nu}_\tau$

0.1 Introduction on particle physics

Quarks

- Quarks are elementary particles
- They are fermions and are forming hadrons
  p = uud, n = udd, $\pi^- = \bar{u}d$, $\pi^+ = u\bar{d}$
- They feel all four interactions,
  strong interaction keeps them together

Flavour Symbol & Name	Mass $[\mathrm{GeV}/c^2]$	Q [e]	J	anti-particle
u, up (ylös)	$\sim 3\times 10^{-3}$	$+2/3$	$1/2$	$\bar{u}$
d, down (alas)	$\sim 3\times 10^{-3}$	$-1/3$	$1/2$	$\bar{d}$
s, strange (outo)	~ 0.1	$-1/3$	$1/2$	$\bar{s}$
c, charm (lumo)	~ 1.2	$+2/3$	$1/2$	$\bar{c}$
b, bottom (pohja)	~ 4.2	$-1/3$	$1/2$	$\bar{b}$
t, top (huippu)	~ 174	$+2/3$	$1/2$	$\bar{t}$

bottom and top quarks may also be called beauty (kauneus) and truth (totuus)

0.1 Introduction on particle physics

Interactions and their carriers

The different interactions are described – in quantum language – by the exchange of characteristic bosons (between the fermion constituents)

The boson force mediators are

Interaction	Mediator	J^π	Mass $[\mathrm{GeV}/c^2]$	Q $[e]$	Relative strength
strong	gluon, g	1^-	0	0	1
electromagnetic	photon, γ	1^-	0	0	10^{-2}
weak	$W^\pm, Z^0$	$1^-, 1^+$	80.4, 91.2	-1,+1, 0	10^{-7}
gravity	graviton, G	2^+	0	0	0

Electromagnetism + weak interaction $\Longrightarrow$ electroweak theory

Electroweak theory + strong interaction $\Longrightarrow$ GUT, Grand Unified Theory

0.1 Introduction on particle physics

Interactions and their carriers

- Strong interaction is responsible for binding quarks together, for example in proton and neutron. It – more accurately, the residual force – also binds protons and neutrons within the nuclei. The force between the quarks is mediated by the massless particle, the gluon.
- Weak interaction processes are responsible for nuclear β-decay. The mediators of the weak interactions are massive $W^{\pm}$ and Z^0 bosons.
- Electromagnetic interactions are responsible for nearly all the phenomena in extra-nuclear physics, i.e. with atoms and molecules. These interactions are mediated by photon exchange.
- Gravitational interactions are supposedly mediated by graviton, a spin-2 boson. It has not yet experimentally observed.

0.1 Introduction on particle physics

High-energy kinematics – 1

In astroparticle physics the energies involved are generally such that relativistic kinematics should be used.

The total energy (E) and mass (m) of the particle are related by

$$E = mc^2$$

where c is the velocity of light ($c \approx 3 \times 10^8$ m/s $=$ 30 cm/ns).

The mass (m) of the particle is given as

$$m = \frac{m_0}{\sqrt{1-\beta^2}} = \gamma m_0, \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

where m_0 is the rest mass and $\beta = v/c$ is the velocity of the particle. The quantity γ is called the Lorentz factor.

0.1 Introduction on particle physics

High-energy kinematics – 2

The total energy (E) can thus also be written as

$$E = \gamma m_0 c^2$$

and $m_0 c^2$ is the rest energy.

The momentum p is

$$p = mv = \gamma m_0 \beta c \qquad (= \beta E/c)$$

The total energy E can also be expressed as

$$E^2 = c^2(p^2 + m_0^2 c^2)$$

This holds for all particles and is a Lorentz-invariant quantity. For massless particles (particles with rest mass zero) it yields

$$E^2 = c^2 p^2$$

0.1 Introduction on particle physics

High-energy kinematics – collisions – 1

For the general case of a collision of two particles with total energy E_1 and E_2 and momentum $\mathbf{p_1}$ and $\mathbf{p_2}$, the Lorentz-invariant center-of-mass energy W can be expressed as

$$W = \sqrt{s} = ... = \left[m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2 \cos\theta) \right]^{1/2}$$

where the angle θ is the angle between $\mathbf{p_1}$ and $\mathbf{p_2}$.

At high energies, β's $\longrightarrow 1$ and $m_1, m_2 \ll E_1, E_2$

Threshold energy for production of particle of mass m:

$$mc^2 \leq W = \sqrt{s}$$

In general, reaction kinematics is easy (easier) to calculate in the center-of-mass than in the laboratory system.

0.1 Introduction on particle physics

High-energy kinematics – collisions – 2

(1) Fixed-target accelerators

Target (particle 2) at rest: $E_2 = m_2 c^2$, $\beta_2 = 0$

The center-of-mass energy is now

$$W = \sqrt{s} = \left[m_1^2 + m_2^2 + 2E_1 m_2 c^2\right]^{1/2} \approx \sqrt{2E_1 m_2 c^2}$$

(2) Colliding-beam accelerators

Particles moving in opposite directions $\Longrightarrow$ $\cos\theta$ = -1 (head-on collision)

The center-of-mass energy is now

$$W = \sqrt{s} = \left[m_1^2 + m_2^2 + 4E_1 E_2 \beta_1 \beta_2\right]^{1/2} \approx 2\sqrt{E_1 E_2}$$

0.1 Introduction on particle physics

High-energy kinematics – collider energies

Example

At the Tevatron collider at Fermilab protons and antiprotons can be accelerated up to the energy of 1 TeV. The center-of-mass energy W is then

$$W = 2\sqrt{E_1 E_2} = 2E = 2 \text{ TeV}$$

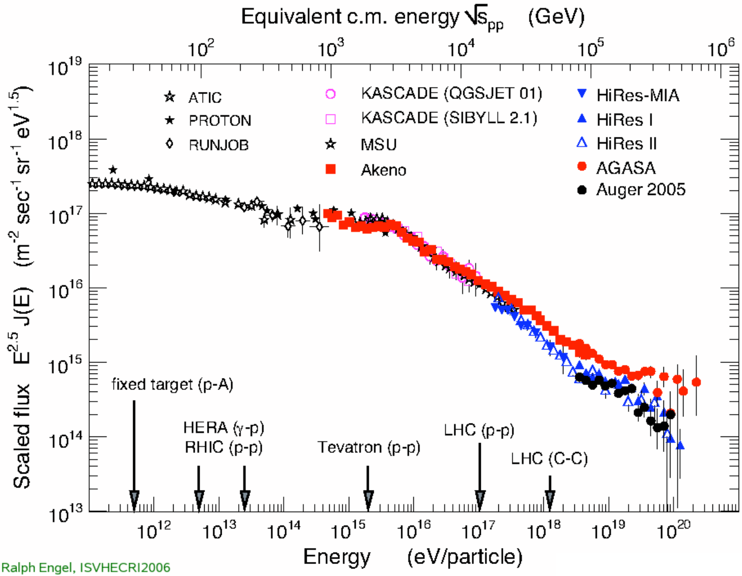
In order to obtain the same center-of-mass energy with a fixed-target accelerator, the energy of the proton beam, in collision with proton target, would have to be

$$E_1 = \frac{s}{2 m_2 c^2} = 2000 \text{ TeV} = 2 \text{ PeV}$$

For comparison: at LHC, $W = 7 \text{ TeV} + 7 \text{ TeV} = 14 \text{ TeV}$

0.1 Introduction on particle physics

Comparison of cosmic-ray and accelerator energies



Ralph Engel, ISVHECRI2006

0.1 Introduction on particle physics

Cross sections

Typical nuclear and particle physics reaction could look as

$$p + {}^{208}\mathrm{Pb} \longrightarrow \mathbf{X} \longrightarrow x + y + z + \ldots$$

The production "probabilities" of **X** and reaction products x, y and z can be described by cross section (σ)

- total cross section (σ_{tot})
- cross section for specific reaction channel (σ_x)
- differential cross sections ($d\sigma/dE$, $d\sigma/d\theta$)

the unit of cross section is defined as the **barn**:
$1\ \mathrm{b} = 10^{-28}\ \mathrm{m} = 10^{-24}\ \mathrm{cm}$ (range generally from pb to mb)

In the most simple case, the cross section can be considered as an effective (overlapping) area that the two particles

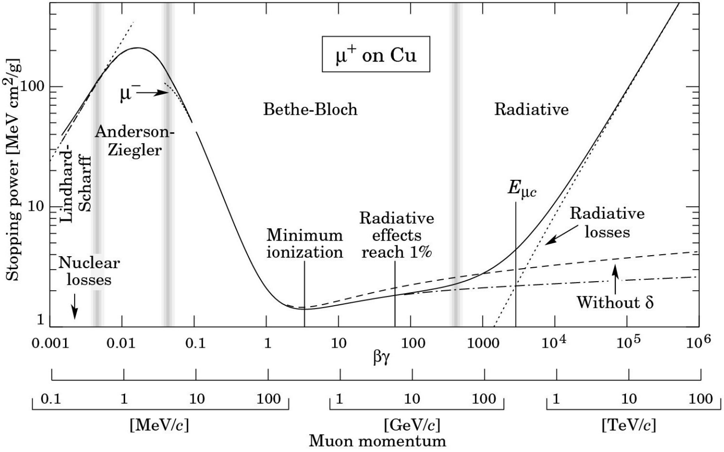
0.2 Detection of astroparticles

Charged particle interactions – intro

- The detection of particles is based on interactions between the incident particle and the detector material
  - several types of interactions, energy dependence
  - (interaction) cross section, σ
- When moving inside the detector material, charged particle interacts (mostly) with electrons of the detector atoms
  - excitations and ionisations of atoms by the particle
    ☞ moving particle experiences an energy loss
  - energy losses also via radiative processes (for example, process of bremsstrahlung)
- The dominating interaction mechanism for moderately relativistic charged particles (not electrons) is energy loss by ionisation and excitation
  - the Bethe–Bloch formula
- Bremsstrahlung important for electrons

0.2 Detection of astroparticles

Charged particle interactions – Energy loss or stopping power



$$\beta\gamma = 10 \Longrightarrow \beta = 0.995$$

$$\beta\gamma = 100 \Longrightarrow \beta = 0.99995 \qquad E_\mu \approx 11 \text{ GeV}$$

$$\beta\gamma = 1000 \Longrightarrow \beta = 0.9999995 \qquad E_\mu \approx 106 \text{ GeV}$$

0.2 Detection of astroparticles

Charged particle interactions – Ionisation and excitation – Bethe–Bloch formula

Moderately relativistic heavy (i.e. other than electrons) charged particles lose energy in matter primarily by ionisation and atomic excitation.

The mean energy loss per distance travelled is given by the Bethe–Bloch formula

$$-\frac{dE}{dx} = K \cdot \frac{z^2 Z}{A} \cdot \frac{1}{\beta^2} \left\{ \frac{1}{2} \ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} \right) - \beta^2 - \frac{\delta}{2} \right\}$$

- I – average ionisation energy of the target, $I \approx Z \cdot 10$ eV
- T_{max} – maximum energy transfer to an electron $= (2 m_e p^2)/(m_0^2 + m_e^2 + 2 m_e E/c^2)$
  - m_0 – (rest) mass of the incident particle
  - p, E – momentum and total energy of the indicent particle
  - $m_e c^2$ – electron rest energy, $m_e c^2 \approx 511$ keV

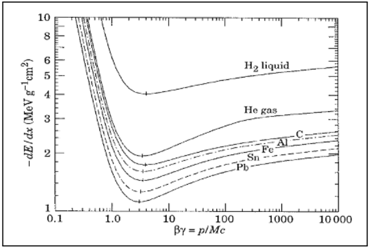
0.2 Detection of astroparticles

Charged particle interactions – Bethe–Bloch formula

- K – $4\pi\ N_A\ r_e^2\ m_e c^2 \approx 0.307\ \frac{\text{MeV}}{\text{g/cm}^2}$
- z – charge number of the incident particle
- β – velocity of the incident particle ($\gamma = 1/\sqrt{1-\beta^2}$)
- Z, A – target charge number and target mass number
- δ – density correction

Characteristics:

- $1/\beta^2$ increase at low energies
- minimum at $\beta\gamma \approx 3.5$ ($\beta \approx 0.96$)
  ☞ minimum ionising particles
- plateau at high energies (for non-gases): $dE/dx \approx 2$ MeV·cm^2·g^{-1}
  ☞ high-energy muon in plastic scintillation detector: $dE/dx \approx 2$ MeV/cm



0.2 Detection of astroparticles

Bremsstrahlung

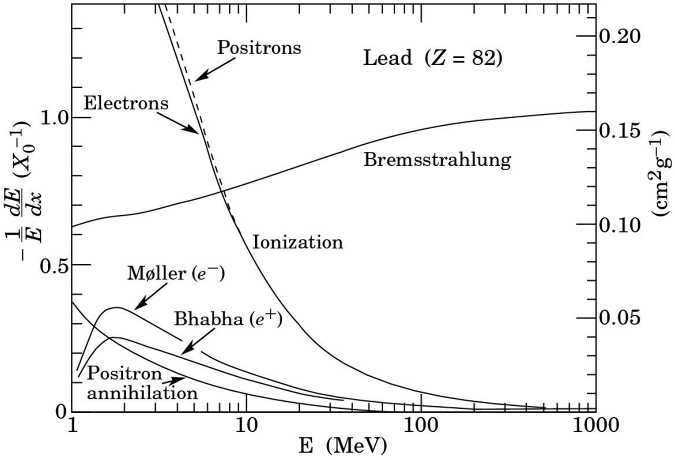
At high energies, the bremsstrahlung becomes significant

$$-\frac{dE}{dx} = 4\alpha \cdot N_A \cdot \frac{Z^2}{A} \cdot r_e^2 \cdot E \cdot \ln\left(\frac{183}{Z^{1/3}}\right) = \frac{E}{X_0}$$

- α – the fine-structure constant ($1/\alpha \approx 137$)
- N_A – Avogadro's number
- r_e – classical electron radius ≈ 2.82 fm
- Other quantities have the same meaning as in the equation for the Bethe–Block formula
- X_0 is called the radiation length

0.2 Detection of astroparticles

Charged particle interactions – electrons



0.3 Detectors in astroparticle physics

Detectors possibilities

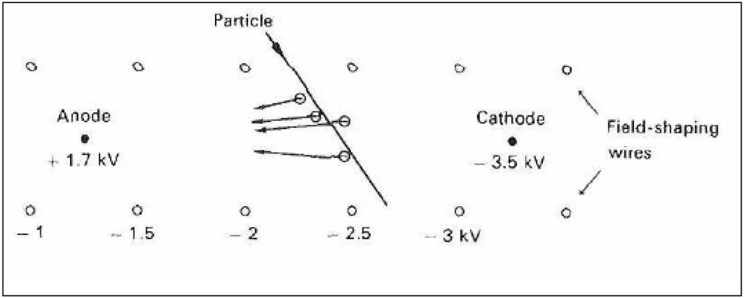
- Proportional counters, drift chambers ($\longrightarrow$ Time Projection Chambers, TPC's)
- Scintillation detectors
- Cherenkov detectors
- Solid-state detectors (Si, Ge)

- Time-of-Flight measurement $\Longrightarrow$ velocity
- Magnetic field combined with tracking $\Longrightarrow$ particle identification (by momentum)
- Calorimetres $\Longrightarrow$ Energy loss

0.3 Detectors in astroparticle physics

Drift chambers

- Drift chambers can provide large detector area with relative good spatial resolution
- Due to the drift of the electron cloud, they are quite slow detectors (μs scale)
- HV usually a few kVolts, chambers filled with gas (Ar, CH_4, CO_2, ...) in $\sim$1 atm



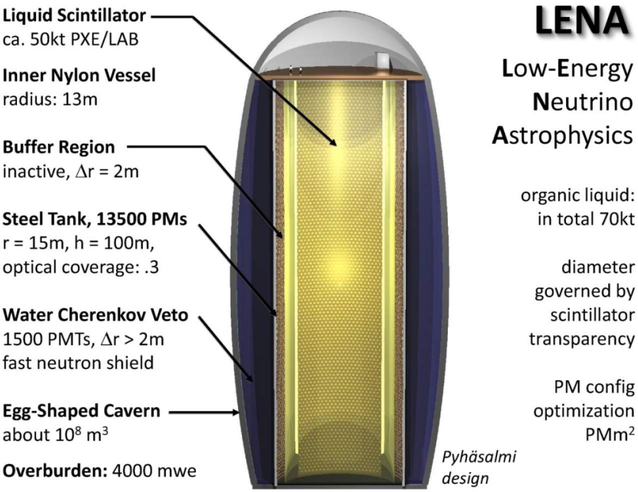
0.3 Detectors in astroparticle physics

Scintillation detectors

- Many types: organic and inorganic crystals, plastics, organic liquids
- Reactions (interactions) produces faint "flashes" of light inside the detector material
  - ☞ light can be detected by photomultiplies tubes (PMTs)
- Very fast (ns scale) and effective detectors but the position resolution not necessarily very good
  - ☞ used generally to produce trigger signal (i.e. "to wake up" the detectors when particles are arriving)
- Astroparticle detectors in the (near) future need to have very large volume (or mass)
  - ☞ liquid is generally low-cost material in kton scale
  - ☞ LENA detector

0.3 Detectors in astroparticle physics

Liquid scintillation detector



0.3 Detectors in astroparticle physics

Cherenkov detector, D_2O

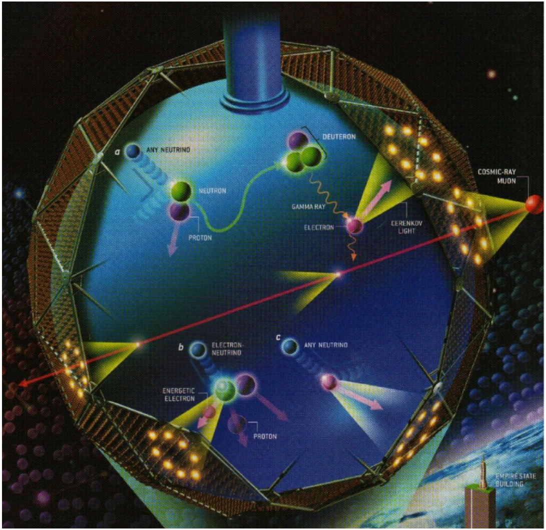
- Pavel Cherenkov 1930's $\longrightarrow$ Cherenkov radiation
- Cherenkov radiation is formed when a charged particle is moving in a medium with a speed that is higher that the speed of light in that same media
  ☞ the velocity $(\beta\gamma)$ of the particle exceeds the refractive index c/n of the media
- The results is "Cherenkov cone"

$$\cos\theta = \frac{1}{\beta n}$$

- For example, n for H_2O is 1.33 $\Longrightarrow \beta \approx 0.75$ can produce Cherenkov radiation

0.3 Detectors in astroparticle physics

Cherenkov detector, D_2O



0.3 Detectors in particle physics

ALICE at LHC