4

(2) The QCD Lagrangian is invariant under local *SU(3)* transformations. i.e. QCD has a local *SU(3)* symmetry. An *SU(3)* transformation is represented by a unitary 3 x 3 matrix with determinant=1.

SU(3) = special unitary group in three dimensions

(3) Approximate conservation of flavour. Quark flavour is conserved at a strong or electromagnetic vertex, but <u>not</u> at a weak vertex.

OZI (Okubo, Zweig and Iizuka) rule
Some <u>strong</u> decays are suppressed

e.g.

$J/\psi = c\bar{c}$ bound state of charmed quarks has anomalously long lifetime

~10^{-20}sec
(Strong decay ~10^{-23}sec)

φ Meson $(s\bar{s})$, $I^G(J^{pc}) = 0^-(1^{--})$

mass = 1020 MeV, Full width $\Gamma = 4MeV$, $(\tau\Gamma = \hbar)$ τ=1.6 x 10^{-22}s

Decay modes

K^+K^-	50%
$K_l^0 K_s^0$	34%
$\rho\pi$	13%
$\pi^+\pi^-\pi^o$	2%
$\eta\gamma$	1%

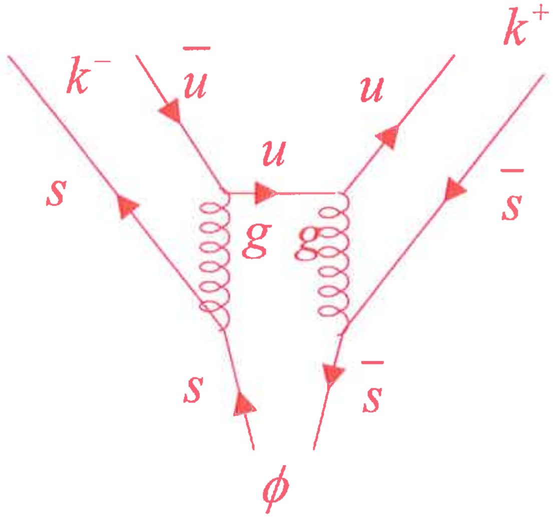
Clearly, ϕ meson decays more often into K^+K^-

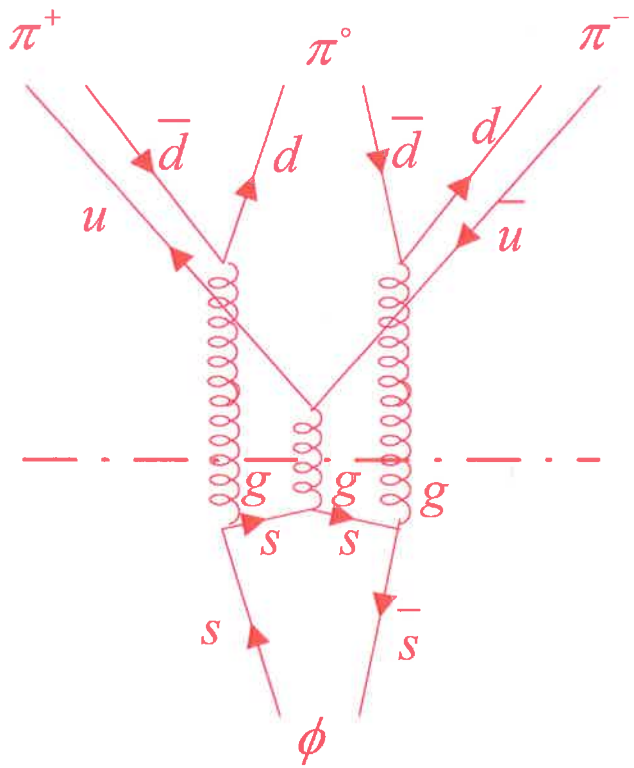
$\phi \to K^+ + K^-$ mass of $(K^+ + K^-) = 990\,MeV/c^2$

than into 3π's

$\phi \to \pi^+ + \pi^- + \pi^0$ mass of $(\pi^+ + \pi^- + \pi^0) = 415\,MeV/c^2$

quark diagrams





OZI rule:

If the diagram can be cut in two by slicing only gluon lines (and not cutting open any external lines), the process is suppressed.

Qualitatively OZI rule is related to the asymptotic freedom.

In an OZI suppressed diagram the gluons have higher energy than those in the OZI - allowed diagram. (More gluons imply higher energy, higher energy so strong interaction coupling constant is smaller, meaning process less likely to occur).

$$J/\psi I^G(J^p) = 0^-(1^-)$$

mass = 3100 MeV/c^2, Γ=0.093 MeV

Decay modes

e^+e^-	6.0%
$\mu^+\mu^-$	6.0%
hadrons	88%

$J/\psi \to 3\pi$ OZI - suppressed

$J/\psi \to D^+ + D^-(D^\circ + \overline{D}^\circ)$ charmed nonstrange Mesons

mass of D $\approx$ 1869 MeV/c^2 . D$^+$ (c $\overline{d}$); D^0 (c $\overline{u}$)

Kinematically forbidden since a pair of two charmed D mesons has larger total mass than the J particle. **Hence this J particle has a longer life time than the ϕ meson.**

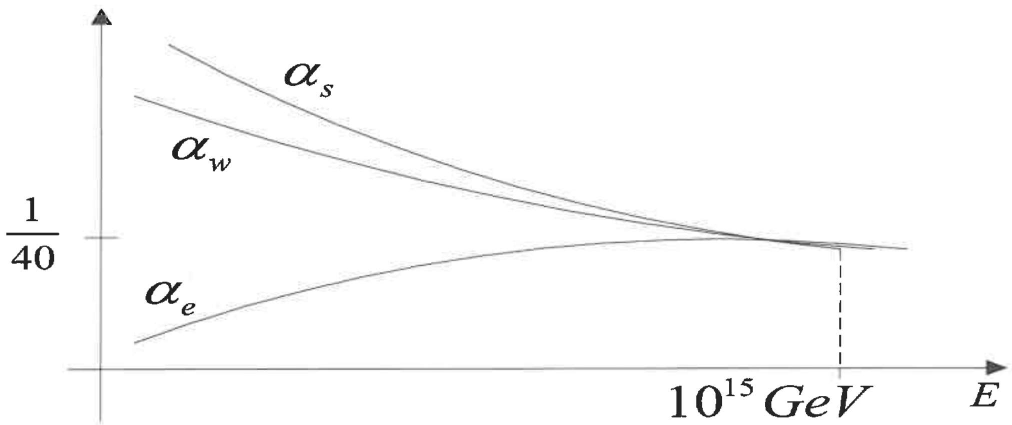
Planck Scale

Strong coupling constant α_s decreases at short distances (very high energy collisions)
Weak coupling α_w also decreases but at a slower rate.

Electromagnetic coupling constant α_e increases as energy increases

[Note: the relative weakness of the weak force is due to the large mass of $W^{\pm}$, Z; its intrinsic strength is greater than that of the ***em*** force.]

From the present functional form of the running coupling constants, α_s, α_w, and α_e converge at around 10^{15} *GeV* (Planck energy scale).



$At\ 10^{-19}\,m,$

$$\alpha_s = \frac{1}{10}$$

$$\alpha_w = \frac{1}{27}$$

$$\alpha_e = \frac{1}{129}$$

$g\bar{\psi}\gamma^{\mu}T^{a}\psi A^{a}_{\mu}$

$= g\, j^{\mu a} A^{a}_{\mu}$

Our Universe according to Wilkison Microwave Anistropy Probe (WMAP) 2003

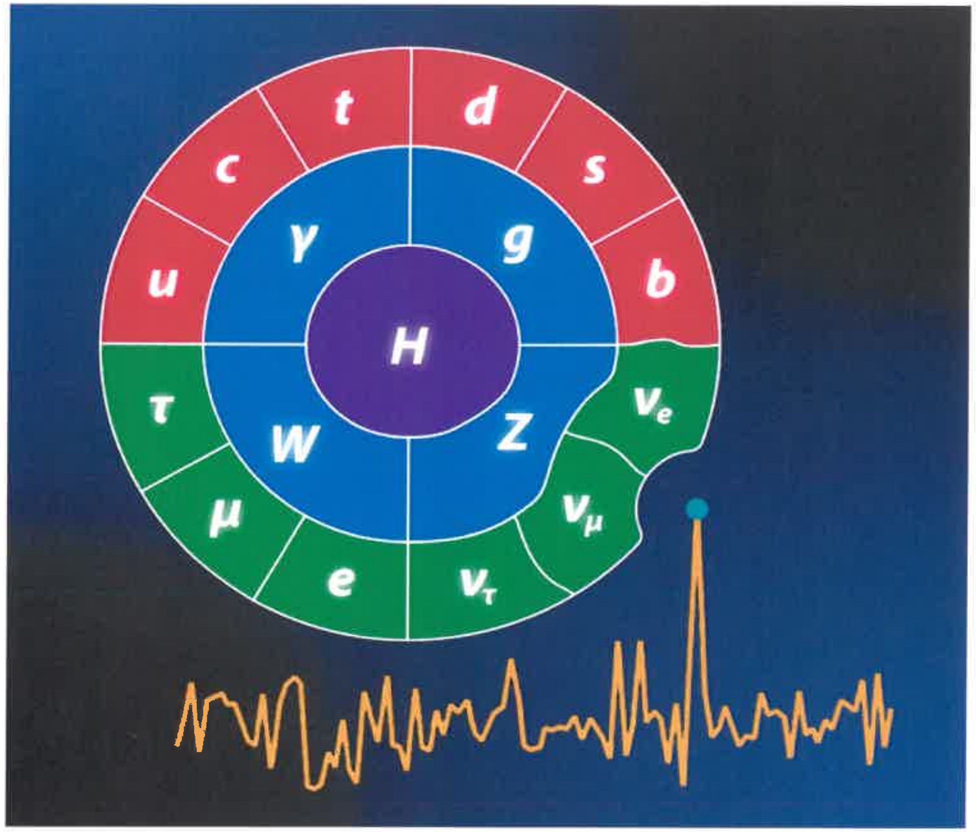
- Age: 13.7 billion years
- Shape: Flat
- Age when first light appeared:200 Million years
- Contents: 4% ordinary matter, 23% dark matter, nature unknown; 73% dark energy, nature unknown
- Hubble constant (expansion rate):71km/sec/megaparsec

To see a World in a Grain of Sand
And a Heaven in A Wild Flower
Hold Infinity in the palm of your hand
And Eternity in an hour

W. Blake (1757-1827)

M.C. Escher

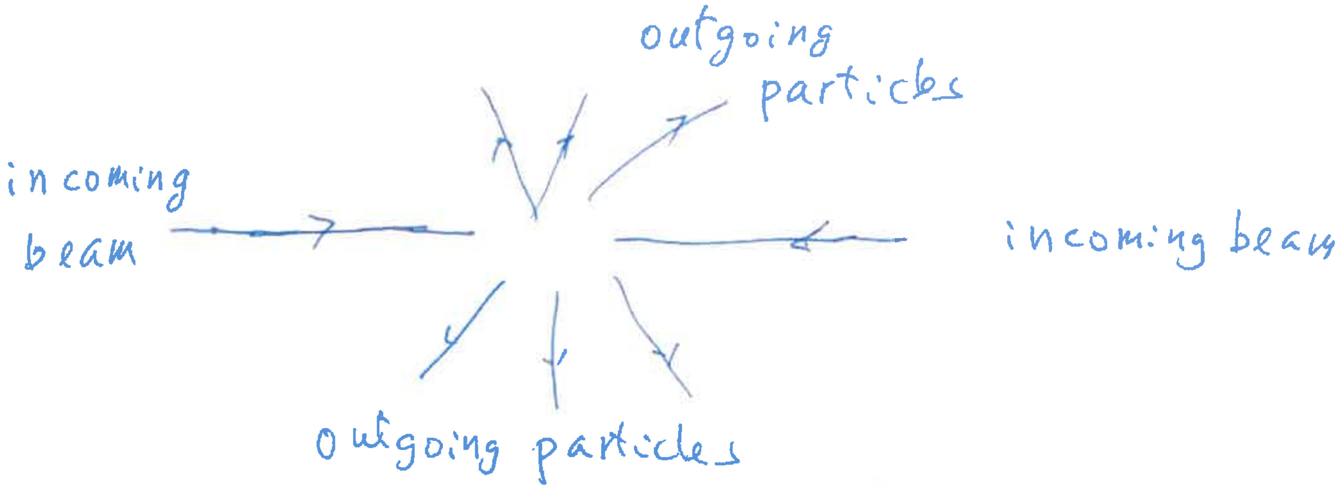
(Dutch graphic artist,
1898- 1972)



APS/Alan Stonebraker
The colored circle represents the standard model of particle physics, which describes the Higgs boson (purple), the force-carrying particles (blue), the quarks (red), and the leptons (green). Particle physicists hope that an anomaly (shown as a data peak) will pierce through the standard model's long-standing dominance, so that a new, more comprehensive theory can develop.

Relativistic Kinematics.

In particle physics, particle reactions involve high energy, e.g in the collider, violent



collisions. Thus the reactions are relativistic

We review special relativity in 4-vector notations and study simple examples in high energy collisions.

Special Relativity:

Frames of reference

Postulates of special Relativity

Galilean and Lorentz transformations

Matrix representation

Definition of general Lorentz transformatio

Metric tensor $g_{\mu\nu}$, $\mu, \nu = 0, 1, 2, 3$.

Frames of reference

Fundamental to the study of physics is frame of reference

Noninertial frames are frames in the presence of external forces, e.g. rotating frames (merry-go-round) or frames under linear acceleration (lifts)

Inertial frames in which external forces are absent, e.g.

A spaceship freely falling in gravitational field experiences no external force is an ideal inertial frame.

Postulates

1. Principle of relativity: All inertial frames of reference are equivalent.

Newtonian relativity: equivalent under Galilean transformations

Newton, Principia 1967

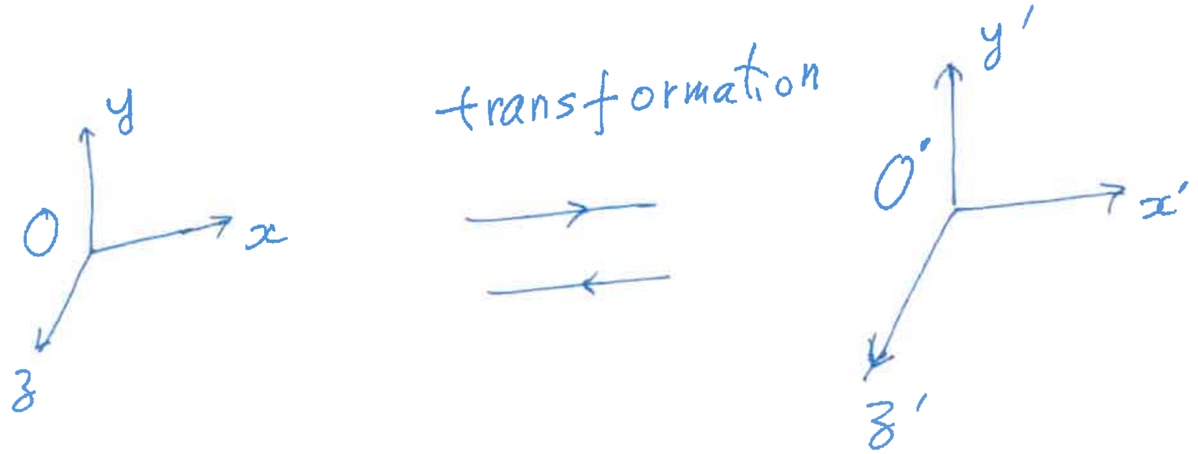
Einsteinian relativity: equivalent under Lorentz transformations

Einstein Special Relativity 1905

2. speed of light c is the same in any inertial frame of reference

Michelson - Morley experiment 1887

Trasformations between two inertial frames O and O'



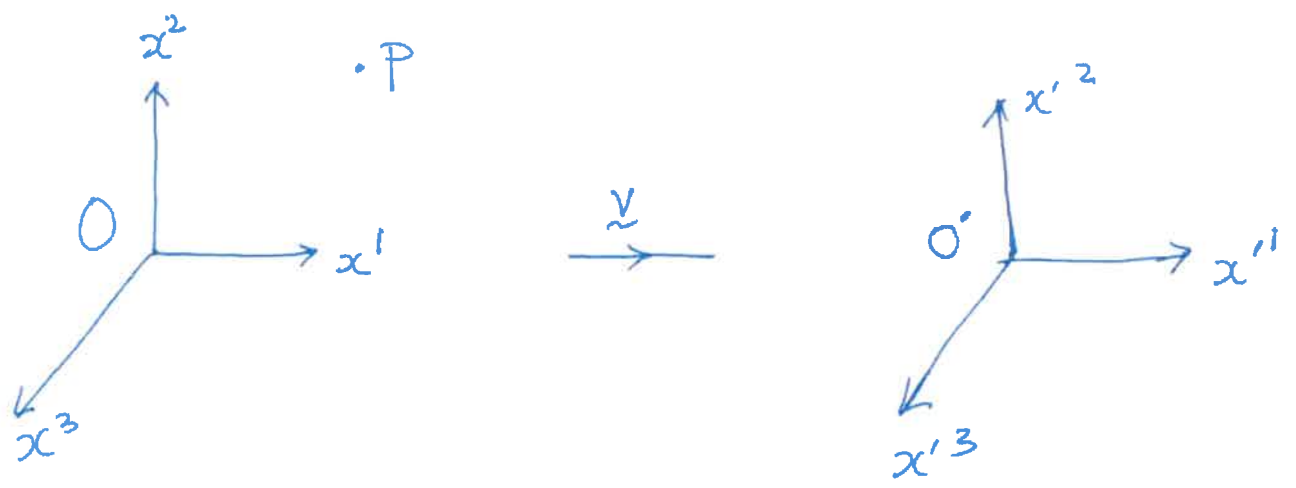
inertial frame O inertial frame O'

For convenience, change x, y, z to x^1, x^2, x^3

and time t to $x^0 \equiv ct$

c = speed of light

Assume at time $t = 0 = t'$, O frame and O' frame coincide with respective axes parallel to each other, also O' frame moves along the x^1-axis of O frame



Consider an event (a particle) at point P of space-time

Coordinates of P in O frame

$(t, \underset{\sim}{x})$, $\underset{\sim}{x} = (x^1, x^2, x^3)$

Coordinates of P in O' frame

$(t', \underset{\sim}{x}')$, $\underset{\sim}{x}' = (x'^1, x'^2, x'^3)$

Galilean transformation

$$\underset{\sim}{x}' = \underset{\sim}{x} - \underset{\sim}{v}\, t$$

$$t' = t$$

$\underset{\sim}{v}$ = velocity of O' frame with respect to O frame

intuitively obvious.

Time is absolute, $t' = t$ (no change)

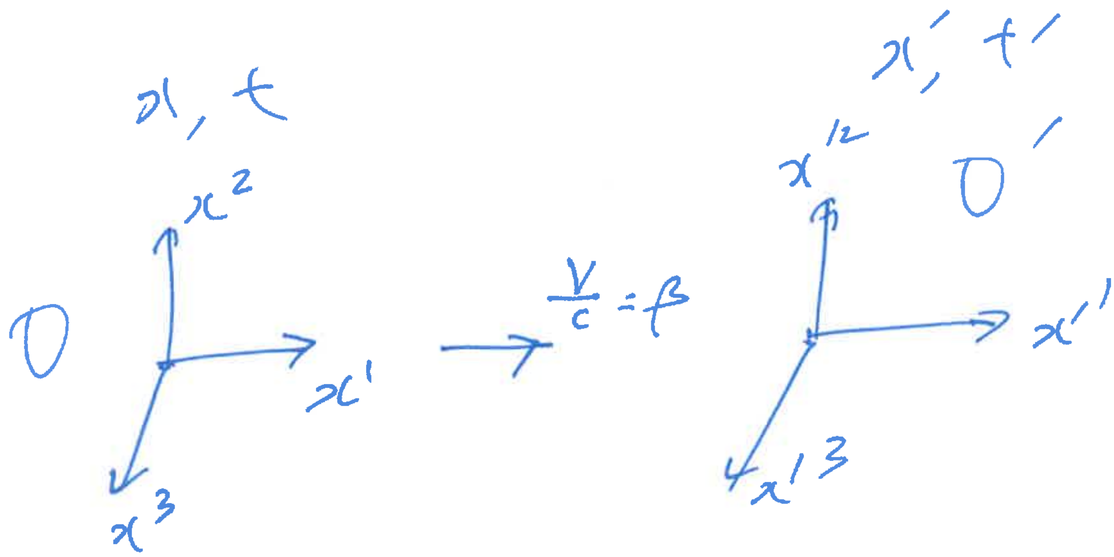
Space is relative, $|\Delta \underset{\sim}{x}'| \neq |\Delta \underset{\sim}{x}|$

Under Galilean transformations, speed of light can be different for different inertial frame observers, but the Michelson - Morley experiment indicates speed of light is constant for all inertial frame observers.

Hence the Galilean transformation is not the right transformation between two inertial frames.

Note that the Newton second law of the motion, the equation of motion $\underset{\sim}{F} = m \ddot{\underset{\sim}{x}}$, is covariant with respect to Galilean transformation, but not the Maxwell equations.

The principle of relativity (all inertial frames of reference are equivalent) together with the requirement that speed of light is constant in inertial frames lead to the Lorentz transformation, which is the right transformation between any two inertial frames.



$$x'^1 = \gamma(x^1 - \beta x^0)$$

$$x'^0 = \gamma(x^0 - \beta x^1)$$

$$x'^2 = x^2 \qquad x'^3 = x^3$$

$$\beta = \frac{v}{c}, \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$c^2 = \frac{1}{\mu_0 \varepsilon_0}$$

Assume at time $t = 0 = t'$, O' frame and O frame coincides with respective axes parallel to each other, also O' frame moves along the x^1-axis of O frame.

The Lorentz transformation is

$$x'^1 = \gamma(x^1 - \beta x^0) \qquad \beta = \frac{v}{c}$$

$$x'^2 = x^2$$

$$x'^3 = x^3 \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$x'^0 = \gamma(x^0 - \beta x^1) \qquad x^0 = ct$$

$$x'^0 = ct'$$

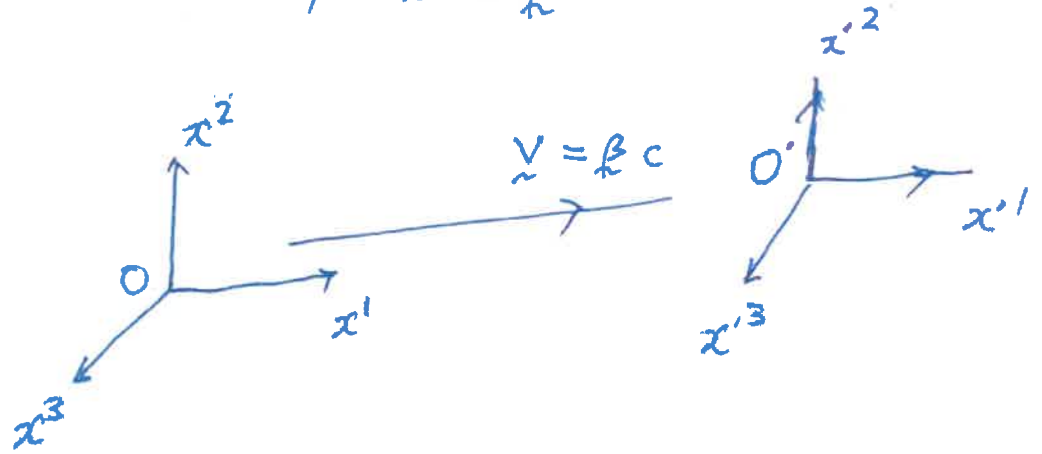
spatial coordinates and time coordinates mix, x'^1 contains x^1 and x^0, x'^0 contains x^0 and x^1.

space and time both relative. →

c (speed of light) is a constant.

Write down Lorentz transformation along any c~~oordinate axis~~ direction, that is $\underset{\sim}{\beta} = \frac{\underset{\sim}{v}}{c}$, not just along x^1-axis

Lorentz transformation along any spatial direction with velocity $\underset{\sim}{v} \equiv \underset{\sim}{\beta} c$



Along x^1-axis

$$x'^1 = \gamma(x^1 - \beta x^0), \quad x'^2 = x^2, \quad x'^3 = x^3$$

$$x'^0 = \gamma(x^0 - \beta x^1). \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Note: spatial components perpendicular to $\underset{\sim}{v}$ unchanged (in this case, x^2, x^3)

Resolve $\underset{\sim}{x} = (x^1, x^2, x^3) = \underset{\sim}{x}_\perp + \underset{\sim}{x}_\parallel$

$$\underset{\sim}{x}_\parallel = \frac{\underset{\sim}{x} \cdot \underset{\sim}{\beta}}{|\underset{\sim}{\beta}|^2} \underset{\sim}{\beta}, \qquad x_\perp \cdot \underset{\sim}{\beta} = 0$$

Thus

$$\underset{\sim}{x}'_\perp = \underset{\sim}{x}_\perp$$

$$\underset{\sim}{x}'_\parallel = \gamma(\underset{\sim}{x}_\parallel - \underset{\sim}{\beta} x^0)$$

$$x'^0 = \gamma(x^0 - \underset{\sim}{\beta} \cdot \underset{\sim}{x})$$