Physics 661

Particle Physics Phenomenology

November 5, 2003

Invariance Principles and Conservation Laws

- Outline
  - Translation and rotation ✓
  - Parity ✓
  - Charge Conjugation
  - Charge Conservation and Gauge Invariance
  - Baryon and lepton conservation
  - CPT Theorem
  - CP violation and T violation
  - Isospin symmetry

Conservation Rules

	Interaction		
Conserved quantity	strong	EM	weak
energy-momentum charge baryon number lepton number	yes	yes	yes
CPT	yes	yes	yes
P (parity)	yes	yes	no
C (charge conjugation parity)	yes	yes	no
CP (or T)	yes	yes	10^{-3} violation
I (isospin)	yes	no	no

Charge Conjugation Invariance

- Charge conjugation reverses sign of charge and magnetic moment, leaving other coord unchanged
- Good symmetry in strong and EM interactions:
  - eg. mesons in p + $\overline{p} \rightarrow \pi^+ + \pi^- + \ldots$
- Only neutral bosons are eigenstates of *C*
- The charge conjugation eigenvalue of the γ is -1:
  - EM fields change sign when charge source reverses sign
- Since $\pi^0 \rightarrow \gamma\gamma$, $C|\pi^0\rangle = +1$
- Consequence of *C* of π^0 and γ, and *C*-cons. in EM int,

  $\pi^0 \rightarrow \gamma\gamma\gamma$ forbidden
  - experiment: $\pi^0 \rightarrow \gamma\gamma\gamma \,/\, \pi^0 \rightarrow \gamma\gamma < 3 \times 10^{-8}$

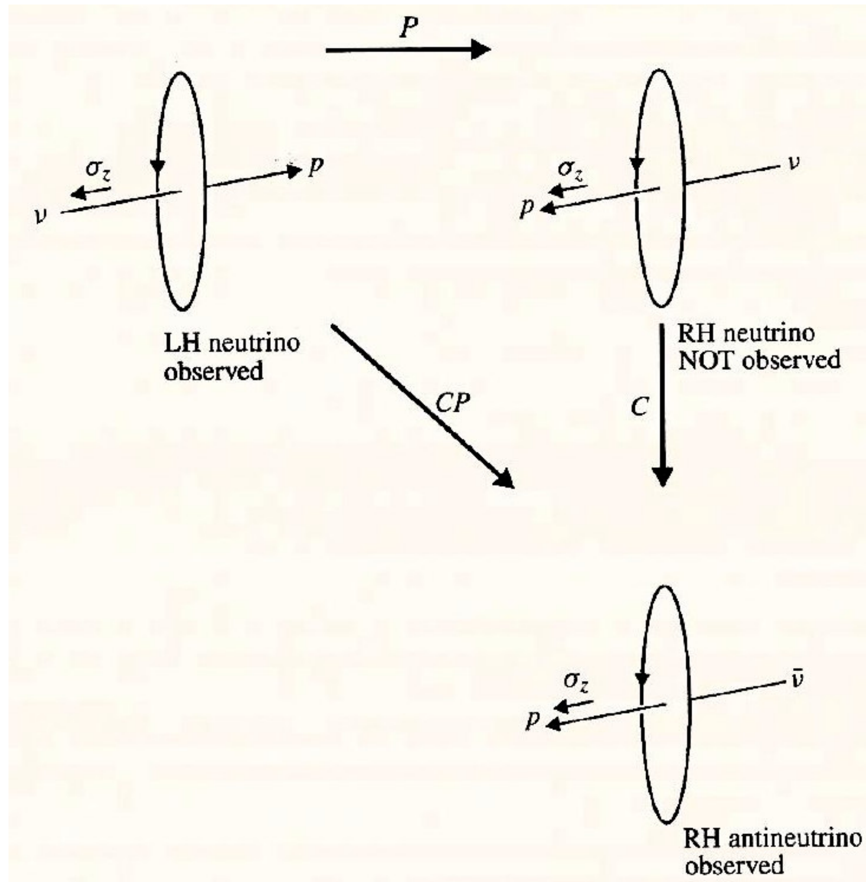
Charge Conjugation Invariance

CHARGE CONJUGATION (C) INVARIANCE

$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{total}$		$<3.1 \times 10^{-8}$, CL = 90%
η C-nonconserving decay parameters		
$\pi^+ \pi^- \pi^0$ left-right asymmetry parameter		$(0.09 \pm 0.17) \times 10^{-2}$
$\pi^+ \pi^- \pi^0$ sextant asymmetry parameter		$(0.18 \pm 0.16) \times 10^{-2}$
$\pi^+ \pi^- \pi^0$ quadrant asymmetry parameter		$(-0.17 \pm 0.17) \times 10^{-2}$
$\pi^+ \pi^- \gamma$ left-right asymmetry parameter		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+ \pi^- \gamma$ parameter β (D-wave)		0.05 ± 0.06 ($S = 1.5$)
$\Gamma(\eta \to 3\gamma)/\Gamma_{total}$		$<5 \times 10^{-4}$, CL = 95%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{total}$	[a]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta \pi^0)/\Gamma_{total}$		$<1 \times 10^{-3}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{total}$		$<3 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \gamma e^+ e^-)/\Gamma_{total}$		$<9 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{total}$	[a]	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{total}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+ \mu^- \pi^0)/\Gamma_{total}$	[a]	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+ \mu^- \eta)/\Gamma_{total}$	[a]	$<1.5 \times 10^{-5}$, CL = 90%

Charge Conjugation Invariance

- Weak interaction
  - respects neither C nor P, but CP is an approximate symmetry of the weak interaction



Charge Conservation Invariance

ELECTRIC CHARGE (Q)

e^- mean life / branching fraction	[o]	$>4.2 \times 10^{24}$ yr, CL = 68%
$\Gamma(n \to p \nu_e \overline{\nu}_e)/\Gamma_{\text{total}}$		$<8 \times 10^{-27}$, CL = 68%

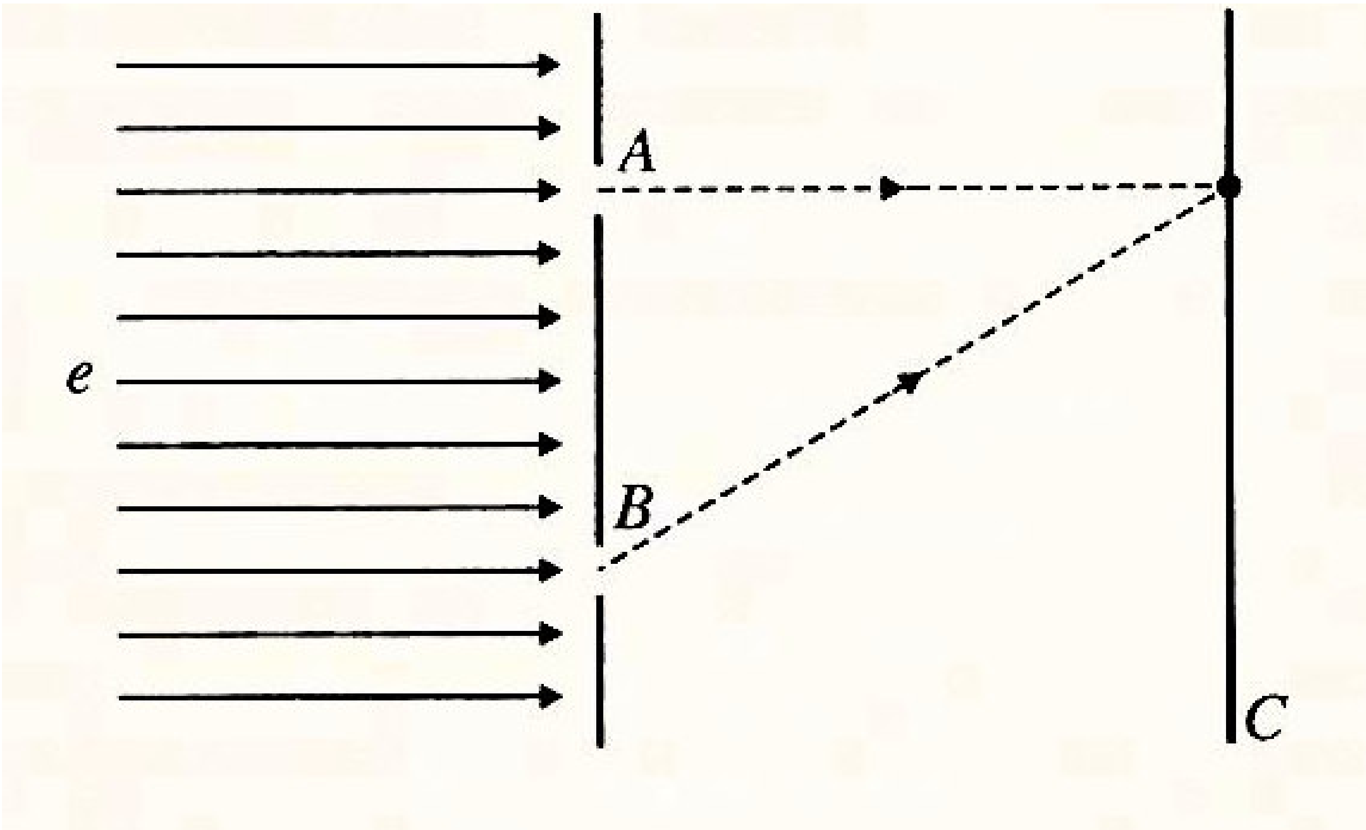
[o] This is the best "electron disappearance" limit. The best limit for the mode $e^- \to \nu\gamma$ is $> 2.35 \times 10^{25}$ yr (CL=68%).

Charge Conservation and Gauge Invariance

- It is possible to described charged particles by wavefuntions with phases chosen arbitrarily at different times and places, provided:
  - the charges couple to a long-range field (the EM field) to which the same local gauge transformation is applied
  - <u>charge is conserved</u>
- This property of local gauge symmetry is a critical ingredient in a field theory that will be renomalizable, such as QED, or the EW theory.

Charge Conservation and Gauge Invariance

- The pattern at C results from the interference of the electrons coming through slits A and B. If we allow an arbitrary phase for each slit, the pattern at C is altered.



Charge Conservation and Gauge Invariance

$$\psi = e^{i(\mathbf{p}\cdot\mathbf{x} - Et)} = e^{ipx}$$

add an arbitrary phase θ, and the space-time gradient of the phase is:

$$\frac{\partial}{\partial x} i(px + e\theta) = i(p + e\frac{\partial\theta}{\partial x})$$

if the phase is local (depends on location), the pattern will be altered; since the electron interacts with the EM field, there is a natural contribution to the phase from the potential

$$\psi = e^{i(p - eA)x}$$

and the space-time gradient of the phase is:

$$\frac{\partial}{\partial x} i(px - eAx + e\theta) = i(p - eA + e\frac{\partial\theta}{\partial x})$$

$$A \rightarrow A + \frac{\partial\theta}{\partial x}$$

Therefore, if the field is transformed locally as the electron, the pattern is unaltered.

Charge Conservation and Gauge Invariance

- It is possible to described charged particles by wavefuntions with phases chosen arbitrarily at different times and places, provided:
  - the charges couple to a long-range field (the EM field) to which the same local gauge transformation is applied
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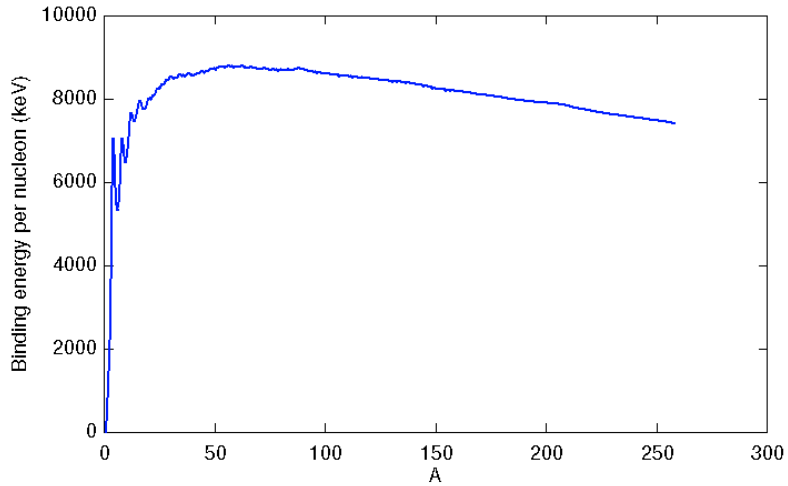
Baryon Conservation

- Baryon number is conserved to a very high level:
  - If it didn't, what would prevent $p \rightarrow e^- \pi^0$?
- Does an underlying long range field lead to this?
  - Equivalency of gravitational and intertial mass established at the 10^{-12} level
  - Since the nuclear binding energy differs with nuclei, the ratio of mass to number of nucleons is not constant, providing a potential source for a difference between gravitational and inertial mass



Baryon Conservation

- Baryon conservation is established to a very low level of violation:
  - $\tau(p \rightarrow e^{+}\pi^{0}) > 10^{33}$ yr
- This is a remarkably precise symmetry, yet we know of no long-range field that could cause it
- We have reason to suspect it is violated at some level:
  - baryon dominance in the Universe today

Baryon Conservation

BARYON NUMBER

$\Gamma(Z \to pe)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{\text{total}}$		$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{\text{total}}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{\text{total}}$		$<3.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{\text{total}}$		$<8.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0\eta)/\Gamma_{\text{total}}$		$<2.7 \times 10^{-5}$, CL = 90%
p mean life		$>1.6 \times 10^{25}$ years

A few examples of proton or bound neutron decay follow. For limits on many other nucleon decay channels, see the Baryon Summary Table.

$\tau(N \to e^+\pi)$		$>$ 158 (n), $>$ 1600 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+\pi)$		$>$ 100 (n), $>$ 473 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to e^+K)$		$>$ 17 (n), $>$ 150 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+K)$		$>$ 26 (n), $>$ 120 (p) $\times 10^{30}$ years, CL = 90%
limit on $n\overline{n}$ oscillations (free n)		$>0.86 \times 10^{8}$ s, CL = 90%
limit on $n\overline{n}$ oscillations (bound n)	[n]	$>1.2 \times 10^{8}$ s, CL = 90%

Lepton Conservation

- Direct searches have not been fruitful:
  - eg. $\tau(^{76}Ge \rightarrow {}^{76}Se + 0\nu + e^- + e^-) > 10^{26}$ yr
    "neutrinoless double beta decay"
- Yet we do observe neutrino oscillations:
  - (eg. $\nu_e \rightarrow \nu_\mu$)
  - these are small transitions

Lepton Conservation

$\Gamma(Z \to e^{\pm}\mu^{\mp})/\Gamma_{total}$	[i]	$<1.7 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to e^{\pm}\tau^{\mp})/\Gamma_{total}$	[i]	$<9.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to \mu^{\pm}\tau^{\mp})/\Gamma_{total}$	[i]	$<1.2 \times 10^{-5}$, CL = 95%
limit on $\mu^- \to e^-$ conversion		
$\sigma(\mu^-\,{}^{32}S \to e^-\,{}^{32}S)$ / $\sigma(\mu^-\,{}^{32}S \to \nu_\mu\,{}^{32}P^*)$		$<7 \times 10^{-11}$, CL = 90%
$\sigma(\mu^-\,Ti \to e^-\,Ti)$ / $\sigma(\mu^-\,Ti \to$ capture$)$		$<4.3 \times 10^{-12}$, CL = 90%
$\sigma(\mu^-\,Pb \to e^-\,Pb)$ / $\sigma(\mu^-\,Pb \to$ capture$)$		$<4.6 \times 10^{-11}$, CL = 90%
limit on muonium $\to$ antimuonium conversion $R_g = G_C\,/\,G_F$		<0.0030, CL = 90%
$\Gamma(\mu^- \to e^-\nu_e\overline{\nu}_\mu)/\Gamma_{total}$	[j]	$<1.2 \times 10^{-2}$, CL = 90%
$\Gamma(\mu^- \to e^-\gamma)/\Gamma_{total}$		$<1.2 \times 10^{-11}$, CL = 90%
$\Gamma(\mu^- \to e^-e^+e^-)/\Gamma_{total}$		$<1.0 \times 10^{-12}$, CL = 90%
$\Gamma(\mu^- \to e^-2\gamma)/\Gamma_{total}$		$<7.2 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^-\gamma)/\Gamma_{total}$		$<2.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\gamma)/\Gamma_{total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-\pi^0)/\Gamma_{total}$		$<3.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\pi^0)/\Gamma_{total}$		$<4.0 \times 10^{-6}$, CL = 90%