Space-Time Symmetries

- Outline
  - Translation and rotation
  - Parity
  - Charge Conjugation
  - Positronium
  - T violation

Conservation Rules

Conserved quantity	Interaction: 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

Discrete and Continuous Symmtries

- Continuous Symmetries
  - Space-time symmetries
  - Lorentz transformations
  - Poincare transformations
    - combined space-time translation and Lorentz Trans.
- Discrete symmetries
  - cannot be built from succession of infinitesimally small transformations -eg. Time reversal, Spatial Inversion
- Other types of symmetries
  - Dynamical symmetries - of the equations of motion
  - Internal symmetries - such as spin, charge, color, or isospin

Conservation Laws

- Continuous symmetries lead to additive conservation laws:
  - energy, momentum
- Discrete symmetries lead to multiplicative conservation laws
  - parity, charge conjugation

Translation and Rotation

- Invariance of the energy of an isolated physical system under space translations leads to conservation of linear momentum

- Invariance of the energy of an isolated physical system under spatial rotations leads to conservation of angular momentum

- Noether's Theorem (Emmy Noether, 1915)

E. Noether, "Invariante Varlationsprobleme", Nachr. d. König. Gesellsch. d. Wiss. zu Göttingen, Math-phys. Klasse (1918), 235-257;

English translation M. A. Travel, Transport Theory and Statistical Physics 1(3) 1971,183-207.

Angular Momentum in Quark Model

Lightest baryon and meson have L=0

So for <u>mesons</u> $J=S(q,\overline{q})=\vec{S}_q+\vec{S}_{\overline{q}}$ for L=0

$$S = \tfrac{1}{2} \pm \tfrac{1}{2} = 0, 1$$

In spectroscopic notation

$$^{2S+1}L_J = {}^1S_0,\ {}^3S_1 \quad (L=0)$$

For L >0 (J=S+L)

L=1 J=0,1,2 for S=1 J=1 for S=0

L=2 J=1,2,3 for S=1 J=2 for S=0

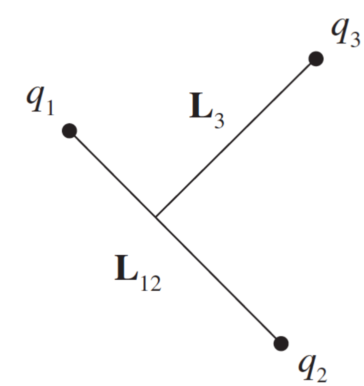
$$^{2S+1}L_J = {}^1L_L,\ {}^3L_{L+1},\ {}^3L_L,\ {}^3L_{L-1} \quad (L\geq 1)$$

Lowest mass states for L=0 -> J=0,1

π,ρ K, K^* D, D^*

Angular Momentum in Quark Model

For <u>baryons</u> $\vec{L} = \vec{L}_{12} + \vec{L}_3$



$$J = \vec{S}(q_1,q_2,q_3) + \vec{L} = \vec{S}_{q1}+\vec{S}_{q2}+\vec{S}_{q3}+\vec{L}$$

$$S = \tfrac{1}{2},\ {}^{3}/_{2} \quad \text{for } L = 0$$

In spectroscopic notation

$$^{2S+1}L_J = \ ^2S_{\frac{1}{2}},\ ^4S_{3/2} \qquad (L=0)$$

$$^{2S+1}L_J = \ ^2P_{\frac{1}{2}},\ ^2L_{3/2},\ ^4L_{\frac{1}{2}},\ ^4L_{3/2},\ ^4L_{5/2} \qquad (L=1)$$

Lowest mass states for L=0 -> J=1/2, 3/2

(p,n), Δ(1232)

Parity

- Spatial inversion
  - $(x,y,z) \rightarrow (-x,-y,-z)$
  - discrete symmetry
- $P\,\psi(r) = \psi(-r)$
  - P is the parity operator
- $P^2\,\psi(r) = P\,\psi(-r) = \psi(r)$,
  - therefore $P^2 = 1$ and the parity of an eigen-system is 1 or -1

Parity

- Example, the spherical harmonics:

Y_L^M

- The spherical harmonics describe a state in a spherically symmetric potential with definite ang. momentum

$$Y_1^0 = \sqrt{\frac{3}{4\pi}} \cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}} \sin\theta e^{i\phi}$$

$$Y_2^0 = \sqrt{\frac{5}{4\pi}} (\tfrac{3}{2}\cos^2\theta - \tfrac{1}{2})$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}} \sin\theta \cos\theta e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}} \sin^2\theta e^{2i\phi}$$

- $p = (-1)^L$

Parity Invariance

PARITY (P) INVARIANCE

e electric dipole moment	$<0.87 \times 10^{-28}$ e cm, CL = 90%
μ electric dipole moment	$(-0.1 \pm 0.9) \times 10^{-19}$ e cm
Re(d_τ = τ electric dipole moment)	-0.220 to 0.45×10^{-16} e cm, CL = 95%
$\Gamma(\eta \to \pi^+\pi^-)/\Gamma_{\text{total}}$	$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 2\pi^0)/\Gamma_{\text{total}}$	$<3.5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to 4\pi^0)/\Gamma_{\text{total}}$	$<6.9 \times 10^{-7}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^+\pi^-)/\Gamma_{\text{total}}$	$<6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0\pi^0)/\Gamma_{\text{total}}$	$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\eta_c(1S) \to \pi^+\pi^-)/\Gamma_{\text{total}}$	$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(\eta_c(1S) \to \pi^0\pi^0)/\Gamma_{\text{total}}$	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta_c(1S) \to K^+K^-)/\Gamma_{\text{total}}$	$<6 \times 10^{-4}$, CL = 90%
$\Gamma(\eta_c(1S) \to K^0_S K^0_S)/\Gamma_{\text{total}}$	$<3.1 \times 10^{-4}$, CL = 90%
p electric dipole moment	$<0.54 \times 10^{-23}$ e cm
n electric dipole moment	$<0.30 \times 10^{-25}$ e cm, CL = 90%
Λ electric dipole moment	$<1.5 \times 10^{-16}$ e cm, CL = 95%

Parity

- Parity is a multiplicative quantum number
- Composite system:
  - parity is equal to product of the parts
  - eg. two pions in an angular momentum L state

$$P = P(\pi_1) \cdot P(\pi_2) \cdot (-1)^L$$

- Intrinsic parity of particles:
  - proton and neutron (+1 by definition, could be -1)
    - parity of fermion and anti-fermion are opposite, and assignment of one is arbitrary
  - pion (-1, measured)

Pion spin and parity

- 1. Spin of the charged pion
  - $p + p \leftrightarrow \pi^+ + d$ $\quad (|M_{if}|^2 = |M_{fi}|^2)$
  - then, "detailed balance" gives:

    $\sigma(pp \to \pi^+ d) \sim (2s_\pi + 1)(2s_d + 1)\, p_\pi^2$

    $\sigma(\pi^+ d \to pp) \sim 1/2\, (2s_p + 1)^2\, p_p^2$

    (1/2 because protons are identical)
  - Measurements of σ's reveals $s_\pi = 0$

- 2. Spin of the neutral pion
  - $\pi^0 \to \gamma\gamma$ shows it must be 0 (see following)

Pion spin and parity

- 2. Spin of the neutral pion
  - $\pi^0 \rightarrow \gamma\gamma$ shows it must be 0
  - along the flight path of the γs in the π^0 rest frame, the total photon spin (S_z) must be 0 or 2
  - If $S_\pi = 1$, then S_z must be 0
  - If $S_\pi = 1$, $S_z = 0$, the two-photon amplitude must behave as $P_l^{m=0}(\cos\ \theta)$, which is antisymmetric under interchange ($=180^0$ rotation)
  - This corresponds to two right or left circularly polarized photons travelling in opposite directions, which must be symmetric by Bose statistics -> forbidden $S_\pi \neq 1$
  - Therefore, $S_\pi = 0$ or $S_\pi \geq 2$ (which is ruled out by pion production statistics - all three charges produced equally)

Parity

- Parity of the charged pion
  - the observation of the reaction

    $\pi^- + d \rightarrow n + n$

    is evidence that the charged pion has p = -1

    assuming parity is conserved

ARGUMENT

- Capture takes place from an s-state, L_i=0 (S_d=1)
  - (X-ray emissions following capture)
- J=1, since S_d=1 and S_π=0

Parity

- Parity of the charged pion
- J=1, since S_d=1 and S_π=0
- In the two neutron system, L+S must be even by the antisymmetric requirement on identical fermions
  - Ψ = Ψ(space) Ψ(spin)
  - S=1 ↑↑, (↑↓+↓↑)/√2, ↓↓ (symmetric)
  - L odd for anti-symmetric wave function
  - S=0 (↑↓−↓↑)/√2 (anti-symmetric)
  - L even for anti-symmetric wave function

    so for J=1, L=1, S=1 is only possibility
  - thus, ${}^{(2S+1)}J_L = {}^3P_1$ state with $p = (-1)^L = -1$
  - since initial state is $p_d p_\pi (-1)^{L_i} = (+1)\ p_\pi$, $p_\pi = -1$

Parity

- Parity of the neutral pion

  $\pi^0 \rightarrow (e^+ + e^-) + (e^+ + e^-)$ (rare decay of the pion)

  - the planes of the pairs follow the E vectors of the internally converted photons ($\pi^0 \rightarrow \gamma\gamma$)
  - even system of two photons (bosons)

  $$A \sim (\mathbf{E}_1 \cdot \mathbf{E}_2) \qquad (P=+1)$$

  $$\text{or } A \sim (\mathbf{E}_1 \times \mathbf{E}_2) \cdot \mathbf{k} \qquad (P=-1)$$

  - Intensities or rates $\sim |A|^2$

  $$|A|^2 \sim \cos^2 \phi$$

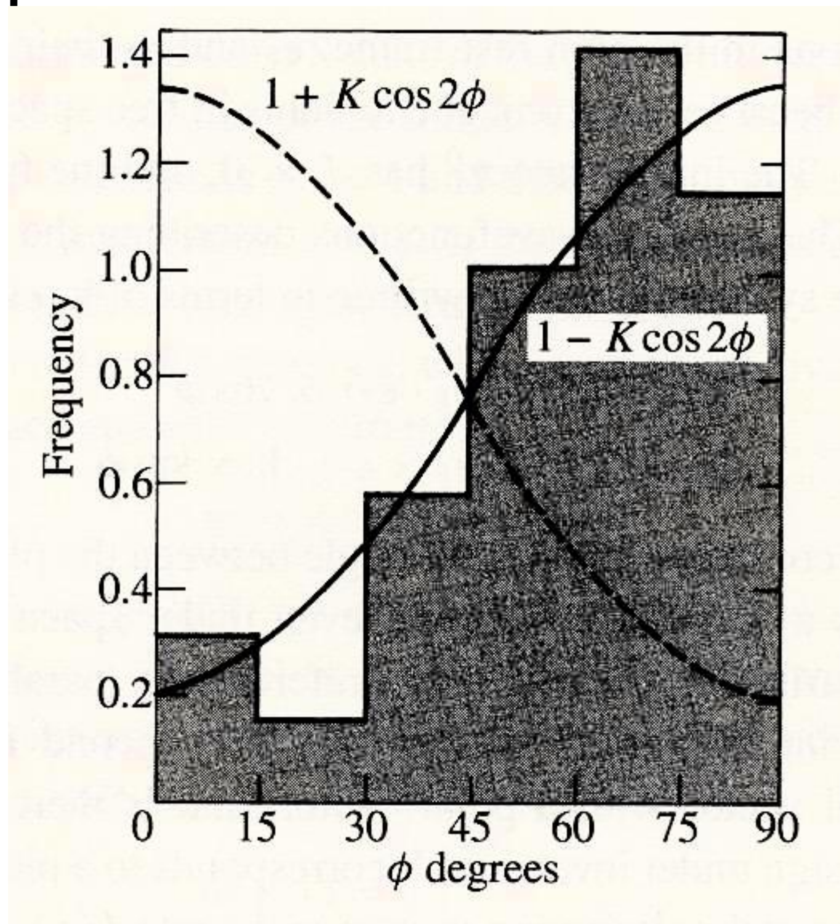
  $$\text{or } |A|^2 \sim \sin^2 \phi$$

Parity

- Parity of the neutral pion

  $\pi^0 \rightarrow (e^+ + e^-) + (e^+ + e^-)$

  scalar(0^+) would follow dashed line, while pseudoscalar (0^-) would follow solid line



Parity of particles and antiparticles

- Two-particle systems
  - Fermion-antifermion
    - $p = (-1)^{L+1}$
    - eg, pion which is q-antiq with L=0 has p = -1
  - Boson-antiboson
    - same parity
    - $p = (-1)^{L}$
    - eg. $\rho \rightarrow \pi^{+}\ \pi^{-}$

      $1^{-} \rightarrow 0^{-}\ 0^{-}$, L=1

Parity of particles and antiparticles

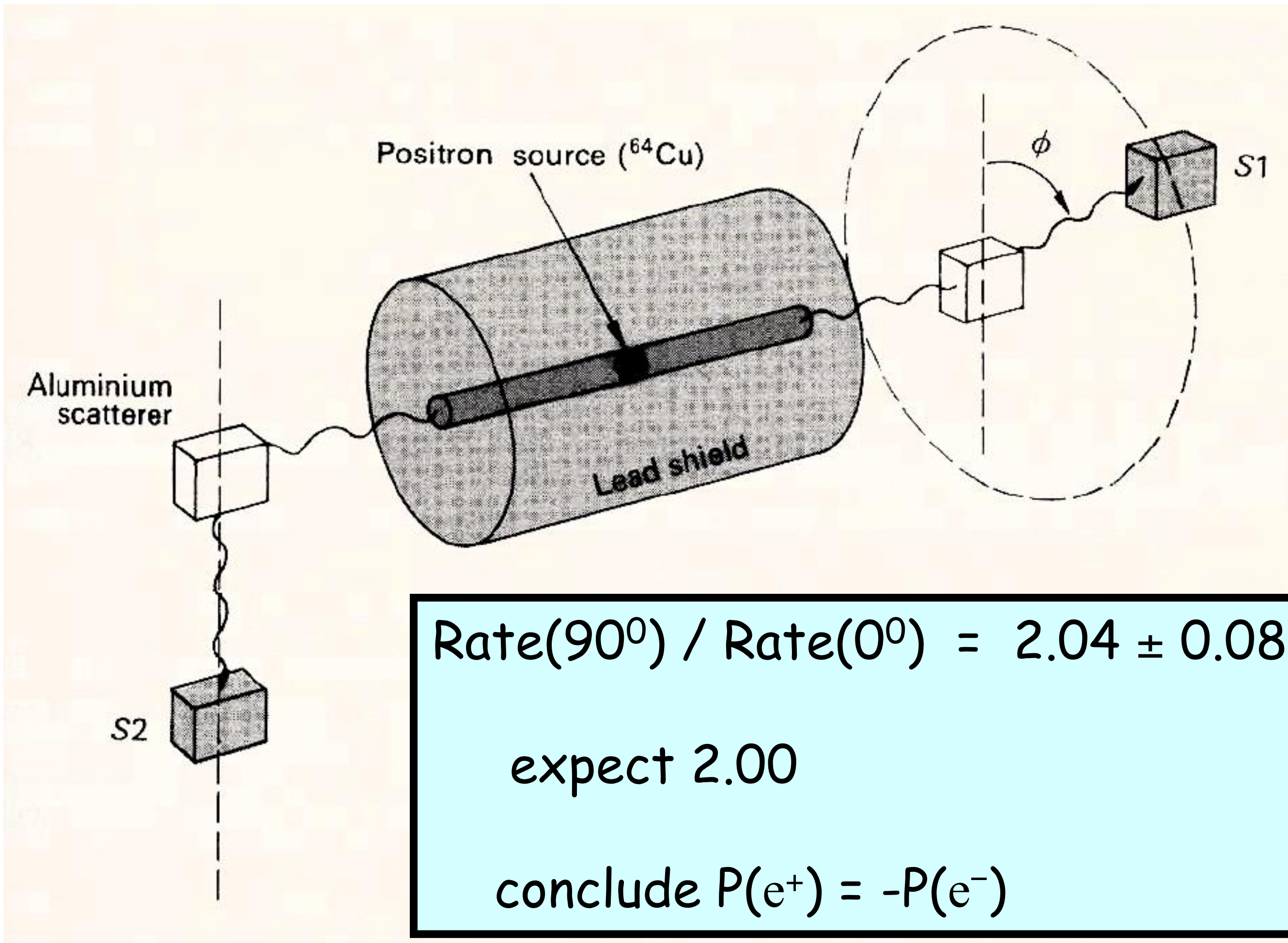
- Dirac theory required fermions and antifermions to have opposite intrinsic parity
- This was checked in decays of the spin singlet ground state of positronium

$$e^+e^- \left({}^{(2S+1)}J_L = {}^1S_0\right) \rightarrow 2\gamma$$

$$P = (+1)\,(-1)\,(-1)^0 = -1$$

- This is exactly the case of the π^0 decay
  - the photon polarizations must have a $\sin^2\phi$ form

Parity of particles and antiparticles



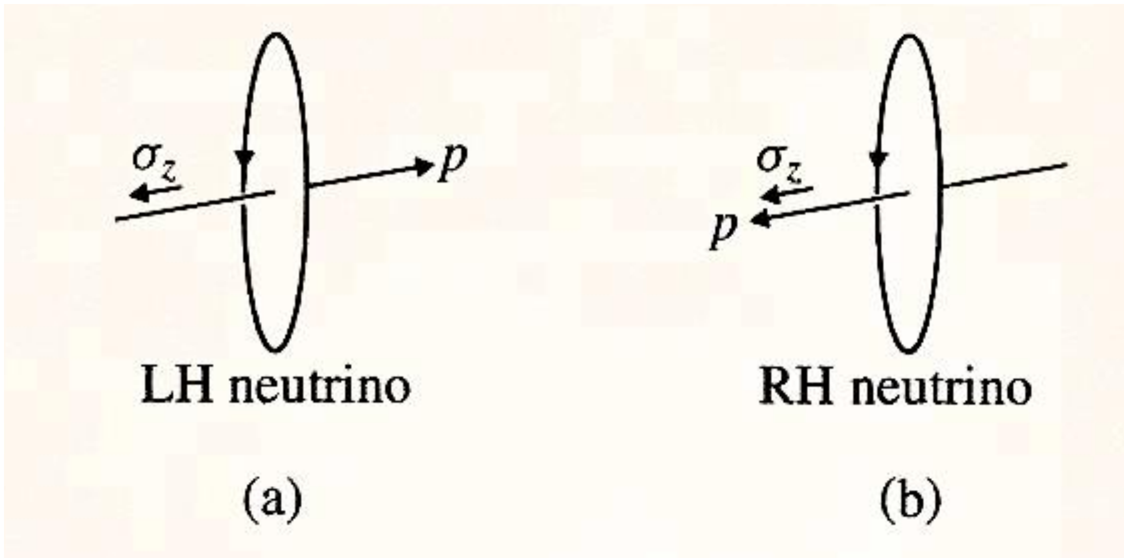
Rate(90^0) / Rate(0^0) = 2.04 ± 0.08

expect 2.00

conclude $P(e^+) = -P(e^-)$

Tests of parity conservation

- Strong and EM interactions conserve parity, but weak interactions do not



- LH neutrino observed, but RH neutrino is not
  - this is a maximally violated symmetry

Tests of parity conservation

- In interactions dominated by the strong or the EM interaction, some parity violation may be observed due to the small contribution of the weak int. to the process

$$H = H_{strong} + H_{EM} + H_{weak}$$

- In nuclear transitions, for example, the degree of parity violation will be of the order of the ratio of the weak to the strong couplings ($\sim 10^{-7}$)

Tests of parity conservation

- Examples of nuclear transitions
  - fore-aft asymmetry in gamma emission

$$^{19}F^* \rightarrow {}^{19}F + \gamma \text{ (110 keV)}$$

$$J^P: \quad 1/2^- \rightarrow 1/2^+$$

$$\Delta \sim (18 +/- 9) \times 10^{-5}$$

  - very narrow decay

$$^{16}O^* \rightarrow {}^{12}C + \alpha$$

$$J^P: \quad 2^- \rightarrow 2^+$$

$$\Gamma = (1.0 +/- 0.3) \times 10^{-10} \text{ eV}$$

(note $^{16}O^* \rightarrow {}^{16}O + \gamma$, $\Gamma = 3 \times 10^{-3}$ eV)

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 $p + \bar{p} \rightarrow \pi^+ + \pi^- + \ldots\ldots$
- 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 of Multiparticles

- Consider $\pi^+ + \pi^-$ (S=0, so J=L)

  $C\,|\pi^+\ \pi^-; L\rangle = |\pi^-\ \pi^+, L\rangle = (-1)^L\,|\pi^+\ \pi^-; L\rangle$

  so $c\,(\pi^+\ \pi^-) = (-1)^L$

- Consider fermion/anti-fermion system

  we can see it is $(-1)^{L+S}$ from the following

  1.) for s=0, l=0, an $f\bar{f}$ system decays to 2 γ's, $c=(-1)^2=+1$

  2.) for s=1, l=0, an $f\bar{f}$ system decays to s=0, l=0 (spin flip) by emitting 1 γ, which is c=-1

  3.) for l>0, the system decays from l to l-1 via EM by emitting 1 γ, which is c=-1

  These observations show only choice is $c=(-1)^{L+S}$

Charge Conjugation of Multiparticles

- Futher considerations on fermion/anti-fermion system

in this case we must consider S, L, and J

$C\,|f\,\overline{f};\,S,L,J\rangle = ?$

L contributes $(-1)^L$

What about S?

S=1 is symmetric and S=0 is antisymmetric

1) ↑↑, (↑↓+↓↑)/√2, ↓↓ 0) (↑↓−↓↑)/√2

so we have $(-1)^{S+1}$

It turns out there is another factor of -1 from QFT,

so we get $(-1)^{L+S}$

(consistent with conclusion on last page)

C & P of particle - antiparticle

- Parity
  - Fermion pair $(-1)^{L+1}$
  - Boson pair $(-1)^{L}$

- Charge conjugation
  - Fermion pair $(-1)^{L+S}$
  - Boson pair $(-1)^{L}$

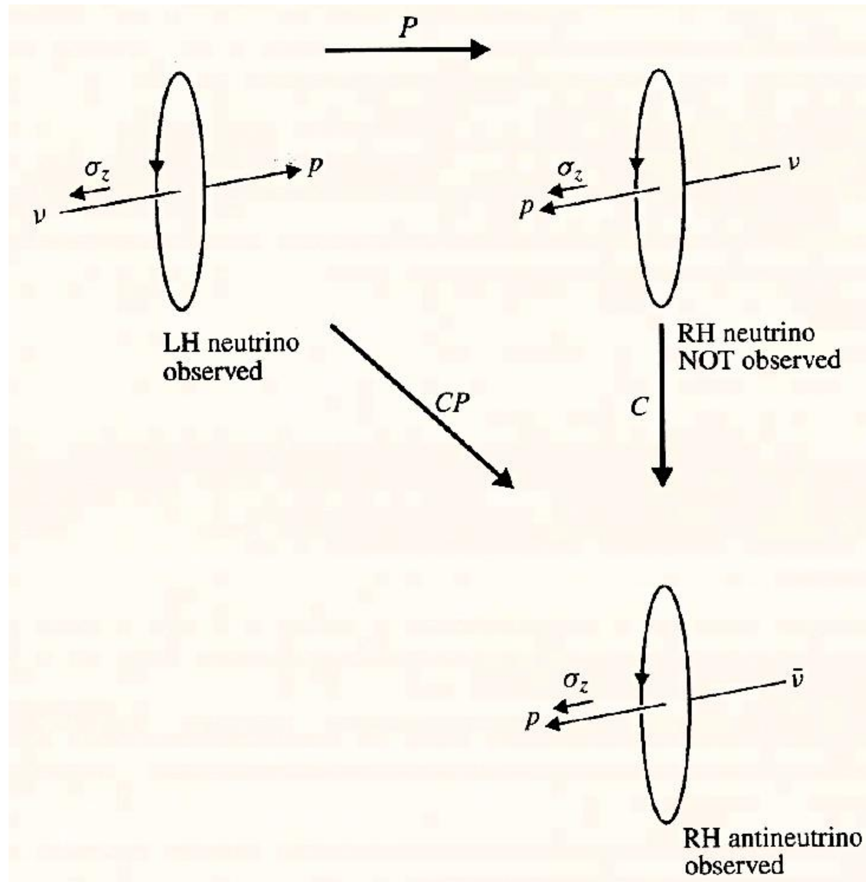
Charge Conjugation Invariance

CHARGE CONJUGATION (*C*) INVARIANCE

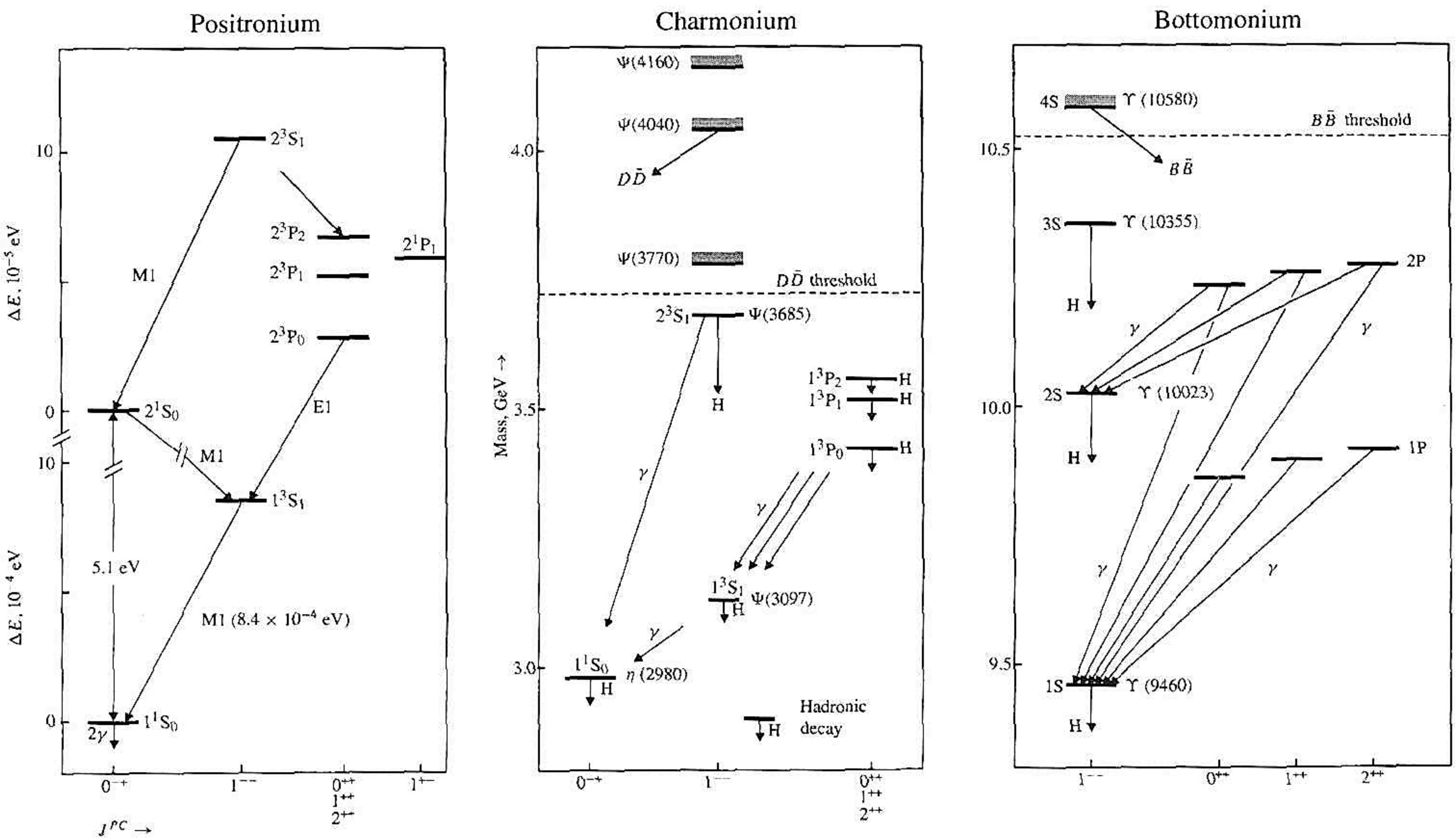
$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{\text{total}}$		$<3.1 \times 10^{-8}$, CL = 90%
η *C*-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry		$(0.09^{+0.11}_{-0.12}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry		$(0.12^{+0.10}_{-0.11}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry		$(-0.09 \pm 0.09) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (*D*-wave)		-0.02 ± 0.07 (S = 1.3)
$\Gamma(\eta \to \pi^0\gamma)/\Gamma_{\text{total}}$		$<9 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 2\pi^0\gamma)/\Gamma_{\text{total}}$		$<5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to 3\pi^0\gamma)/\Gamma_{\text{total}}$		$<6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 3\gamma)/\Gamma_{\text{total}}$		$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[*a*]	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{\text{total}}$	[*a*]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{\text{total}}$		$<2.1 \times 10^{-4}$, CL = 90%
$\Gamma(\omega(782) \to 2\pi^0)/\Gamma_{\text{total}}$		$<2.1 \times 10^{-4}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{\text{total}}$		$<2.3 \times 10^{-4}$, CL = 90%
asymmetry parameter for $\eta'(958) \to \pi^+\pi^-\gamma$ decay		-0.03 ± 0.04
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[*a*]	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{\text{total}}$	[*a*]	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{\text{total}}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\pi^0)/\Gamma_{\text{total}}$	[*a*]	$<6.0 \times 10^{-5}$, CL = 90%

Charge Conjugation Invariance

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



Quarkonium and Positronium



Positronium

- Bound state of electron and positron
- $V(r) = -\alpha/r$
- $E_n = -m_r \alpha^2/2n^2 = -13.6$ ev $/2n^2$

$E_1 = -6.8$ eV $E_2 = -1.7$ eV $\Delta E = 5.1$ eV

- Each principal level n state has
  - $S = 0$ or 1
  - $L = 0, \ldots n-1$ (so $L=0$ for $n=1$, $L=0$ or 1 for $n=2$)
- Parity and C-parity of each level
  - $P = P_{e-} P_{e+} (-1)^L = (-1)^{L+1}$
  - $C = (-1)^{L+S}$

Positronium

- Principal energy levels from non-relativistic Schroedinger equation in a Coulomb potential

$$E_n = -\alpha^2 \mu c^2 / 2n^2, \quad \mu = m/2$$

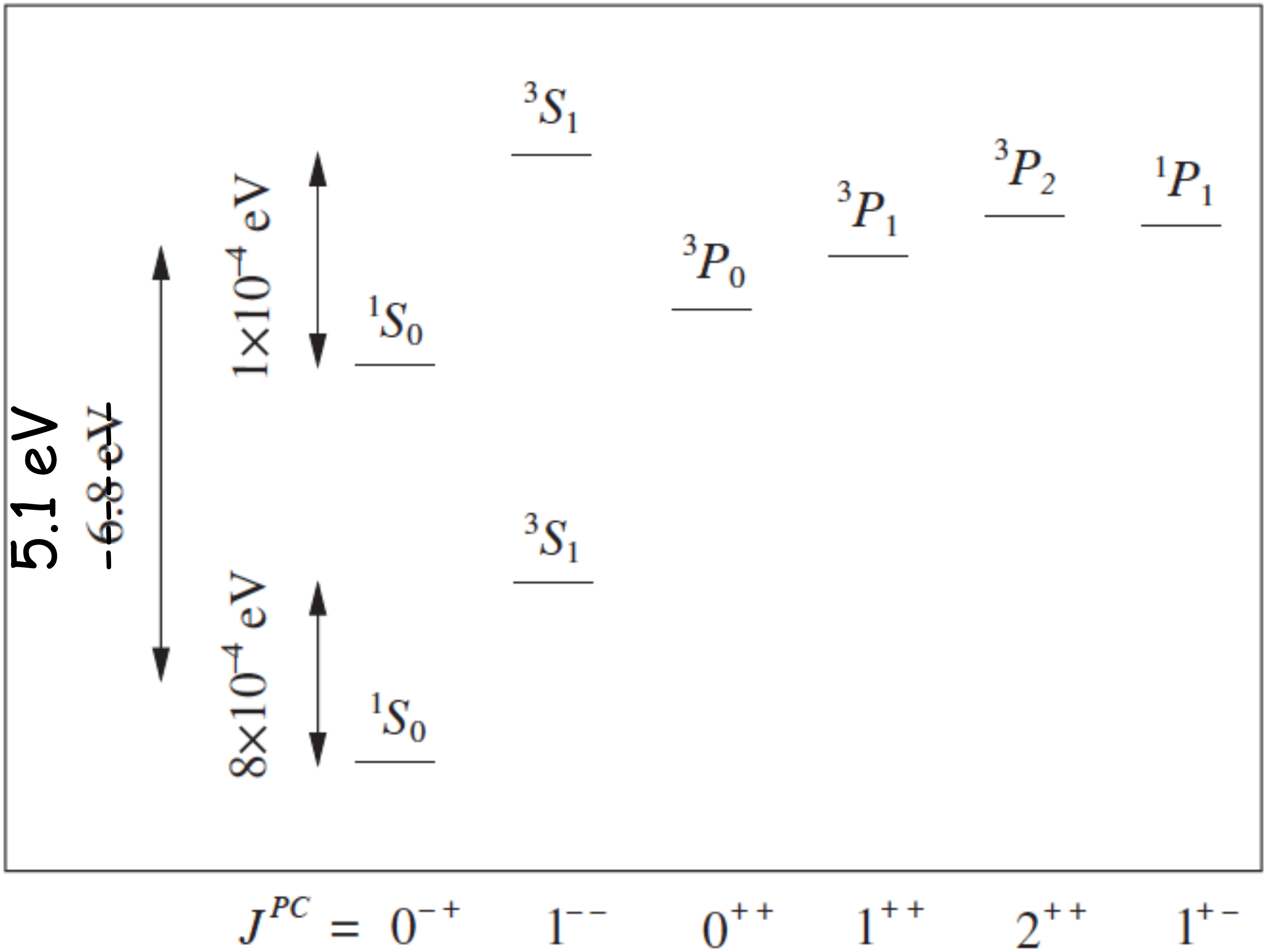
- Relativistic corrections:
  - spin-orbit
    - S, P, D
  - spin-spin
    - $^3S_1$, $^1S_0$, ……
  - these are about the same size in positronium:
    - $\Delta E \sim \alpha^4 mc^2 / n^3$

Positronium

- Fine structure
  - Orthopositronium/parapositronium splitting
  - $E(n=1, {}^3S_1) - E(n=1, {}^1S_0) = 8.45 \times 10^{-4}$ eV
- There are two contributions
  1) spin-spin - magnetic moment of positron gives rise to B field which interacts with the magnetic moment of the electron
     - Depends on relative alignment of spins
  2) one-photon exchange
     shifts only ${}^3S_1$ state

- Total shift for n=1
  - $7/6\ \alpha^2$ (13.6 eV) = 0.000845 eV

Positronium



Positronium

- Lifetimes:
  - Two photon ($C=(-1)^2 = 1$)
    - two photons means rate is to order α^2
    - overlap of wavefunctions at origin to annihilate
      - $|\psi(0)|^2 = 1/ \pi a^3$
      - $a = 2 h/(2\pi mc \alpha)$
    - exact result:
      - $\Gamma = \alpha^5 m/2$
  - Three photon ($C=(-1)^3 = -1$)
    - rate at higher order
      - $\Gamma = 2(\pi^2-9) \alpha^6 m/(9\pi)$

Positronium

- e^+e^- -> $\gamma\gamma$
  - $\tau = 1.25 \times 10^{-10}$ sec
  - singlet state
  - even ang. momentum -> J=0 -> $C = (-1)^{L+S} = (-1)^0 = +1$
  - $C = (-1)^{n\gamma}$ -> $C = +1$

- e^+e^- -> $\gamma\gamma\gamma$
  - $\tau = 1.4 \times 10^{-7}$ sec
  - triplet state -> J=1 -> $C = (-1)^{L+S} = (-1)^{0+1} = -1$
  - $C = (-1)^{n\gamma}$ -> $C = -1$

C & P of e+e- system

- Interchange of particles
  - Spin symmetry $(-1)^{S+1}$

    eg. $\alpha(s=0, s_3=0) = 1/\sqrt{2}\,(\uparrow\downarrow - \downarrow\uparrow)$
  - Spatial symmetry $(-1)^{L+1}$
    - Recall opposite intrinsic parities of e+ and e-
  - So – total symmetry is $(-1)^{L+S}$
- Interchange of space and spin

  is equivalent to Charge Conjugation

Positronium

- Excellent agreement on Theory and Experimental results for lifetimes and energy levels

Table 4.4. *Positronium lifetimes and level spacings*

	Theory	Experiment
$e^+e^- \to 2\gamma$ rate	$(7.985 \pm 0.002) \times 10^9\ \mathrm{s}^{-1}$	$(7.99 \pm 0.11) \times 10^9\ \mathrm{s}^{-1}$
$e^+e^- \to 3\gamma$ rate	$(7.0386 \pm 0.0004) \times 10^6\ \mathrm{s}^{-1}$	$(7.05 \pm 0.01) \times 10^6\ \mathrm{s}^{-1}$
$(\Delta E/h)(1^3\mathrm{S}_1–1^1\mathrm{S}_0)$	$203\,400 \pm 10$ MHz	$203\,386 \pm 2$ MHz
$(\Delta E/h)(2^3\mathrm{S}_1–2^3\mathrm{P}_2)$	8625 ± 10 MHz	8629 ± 6 MHz

Time reversal

- $t \rightarrow t' = -t$
- Symmetry of strong and EM interactions, but violated by weak interaction

Time reversal violation

			Effect of T	Effect of P
•	position	r	r	−r
•	momentum	p	−p	−p
•	spin	σ = (r × p)	$-\sigma$	σ
•	electric field	E (= $-\nabla$V)	E	−E
•	magnetic field	B	−B	B
•	mag. dip. mom.	$\sigma \cdot B$	$\sigma \cdot B$	$\sigma \cdot B$
•	el. dipl. mom.	$\sigma \cdot E$	$-\sigma \cdot E$	$-\sigma \cdot E$
•	long. pol.	$\sigma \cdot p$	$\sigma \cdot p$	$-\sigma \cdot p$
•	trans. pol.	$\sigma \cdot (p_1 \times p_2)$	$-\sigma \cdot (p_1 \times p_2)$	$\sigma \cdot (p_1 \times p_2)$

Time Reversal Invariance

TIME REVERSAL (T) INVARIANCE

e electric dipole moment		$<0.87 \times 10^{-28}$ e cm, CL $= 90\%$
μ electric dipole moment		$(-0.1 \pm 0.9) \times 10^{-19}$ e cm
μ decay parameters		
transverse e^+ polarization normal to plane of μ spin, e^+ momentum		$(-2 \pm 8) \times 10^{-3}$
α'/A		$(-10 \pm 20) \times 10^{-3}$
β'/A		$(2 \pm 7) \times 10^{-3}$
Re($d_\tau = \tau$ electric dipole moment)		-0.220 to 0.45×10^{-16} e cm, CL $= 95\%$
P_T in $K^+ \to \pi^0 \mu^+ \nu_\mu$		$(-1.7 \pm 2.5) \times 10^{-3}$
P_T in $K^+ \to \mu^+ \nu_\mu \gamma$		$(-0.6 \pm 1.9) \times 10^{-2}$
Im(ξ) in $K^+ \to \pi^0 \mu^+ \nu_\mu$ decay (from transverse μ pol.)		-0.006 ± 0.008
asymmetry A_T in K^0-$\overline{K}^0$ mixing		$(6.6 \pm 1.6) \times 10^{-3}$
Im(ξ) in $K^0_{\mu 3}$ decay (from transverse μ pol.)		-0.007 ± 0.026
$A_T(D^\pm \to K^0_S K^\pm \pi^+ \pi^-)$	[b]	$(-12 \pm 11) \times 10^{-3}$
$A_T(D^0 \to K^+ K^- \pi^+ \pi^-)$	[b]	$(1.7 \pm 2.7) \times 10^{-3}$
$A_T(D^\pm_s \to K^0_S K^\pm \pi^+ \pi^-)$	[b]	$(-14 \pm 8) \times 10^{-3}$
ΔS^+_T $(S^-_{\ell^-,K^0_S} - S^+_{\ell^+,K^0_S})$		-1.37 ± 0.15
ΔS^-_T $(S^+_{\ell^-,K^0_S} - S^-_{\ell^+,K^0_S})$		1.17 ± 0.21
ΔC^+_T $(C^-_{\ell^-,K^0_S} - C^+_{\ell^+,K^0_S})$		0.10 ± 0.16

T Violation

- Transverse polarization

		Effect of T	Effect of P
• trans. pol.	$\sigma\bullet(p_1 \times p_2)$	$-\sigma\bullet(p_1 \times p_2)$	$\sigma\bullet(p_1 \times p_2)$

- $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$
- $n \rightarrow p + e^- + \overline{\nu}_e$
  - T-violating contributions below 10^{-3}

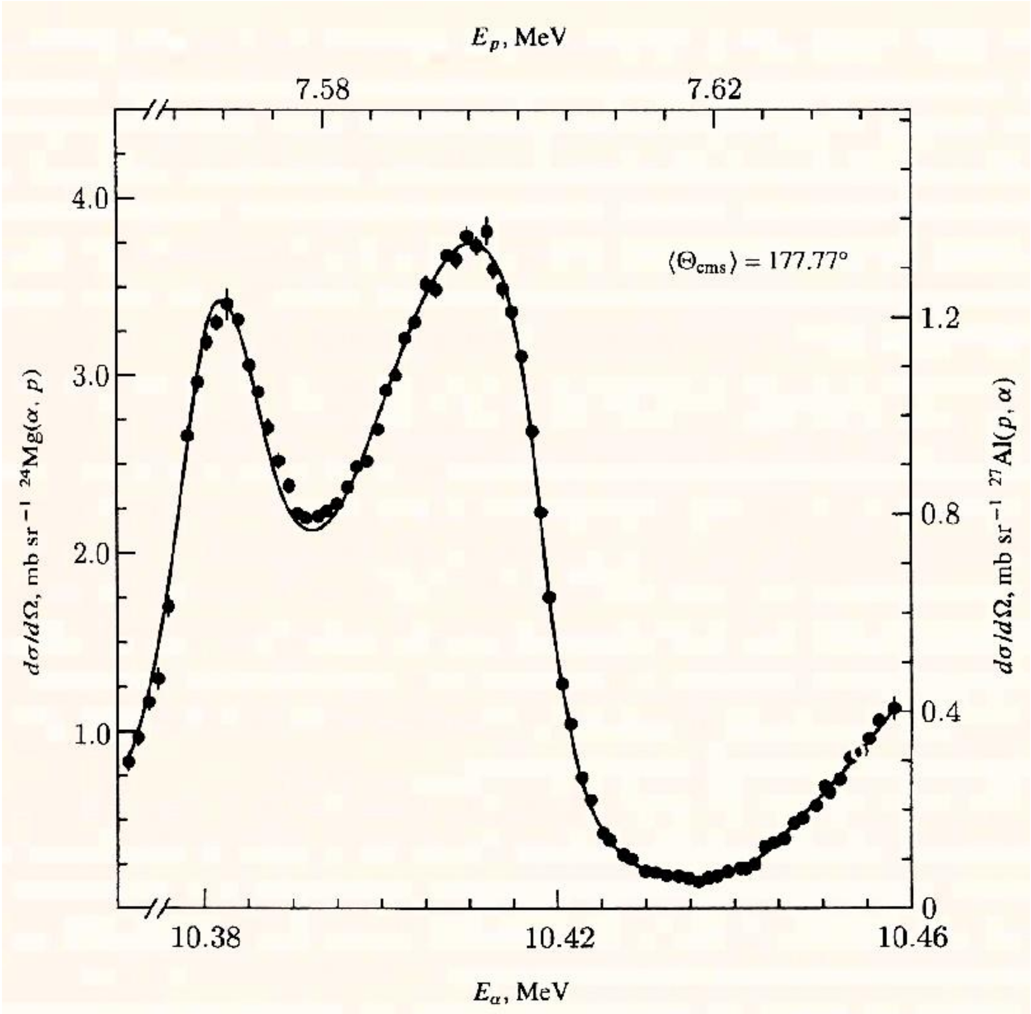
T Violation

- Detailed Balance

$p + {}^{27}Al \leftrightarrow \alpha + {}^{24}Mg$

curve and points

T violation
$< 5 \times 10^{-4}$



Neutron Electric Dipole Moment

- Most sensitive tests of T violation come from searches for the neutron and electron dipole moments

  - electron $< 0.87 \times 10^{-28}$ e-cm
  - neutron $< 0.29 \times 10^{-25}$ e-cm

- Note, the existence of these electric dipole moments would also violate parity

Neutron Electric Dipole Moment

- How big might we expect the EDM to be?
  - EDM = (charge x length) x T-violating parameter

    length ~ 1/Mass

    assume weak interaction - $\sim g^2 / M_W^2$

    $\sim e^2 M_N / M_W^2 \sim 4\pi/137\ (0.94\ \text{GeV}) / (80\text{GeV})^2$

    $\sim 10^{-5}\ \text{GeV}^{-1}$ [200 MeV-fm]

    $\sim 10^{-6}\ \text{fm} \sim 10^{-19}\ \text{cm}$

    T-violating parameter $\sim 10^{-3}$ (like K^0)

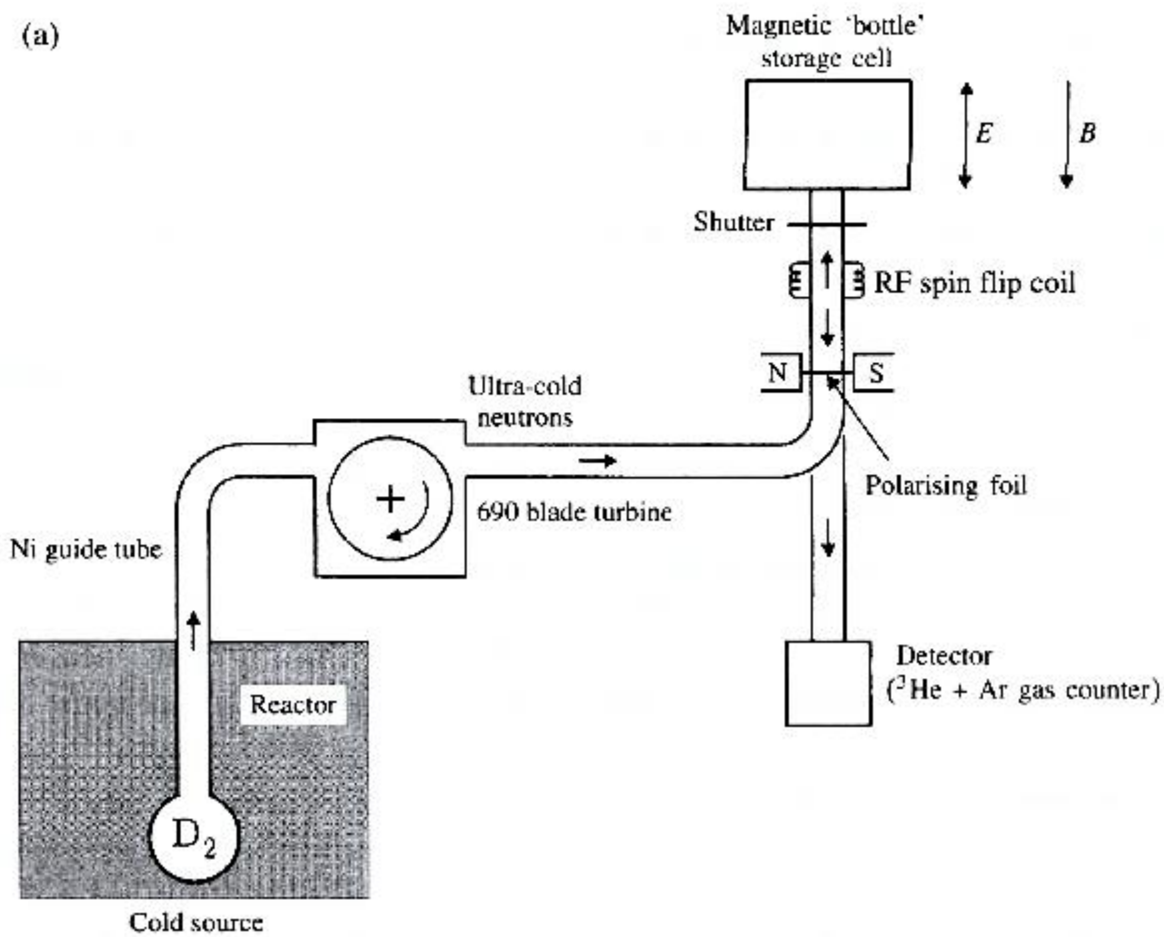
    Then:

    EDM $\sim e\ (10^{-19}\ \text{cm})(10^{-3})$

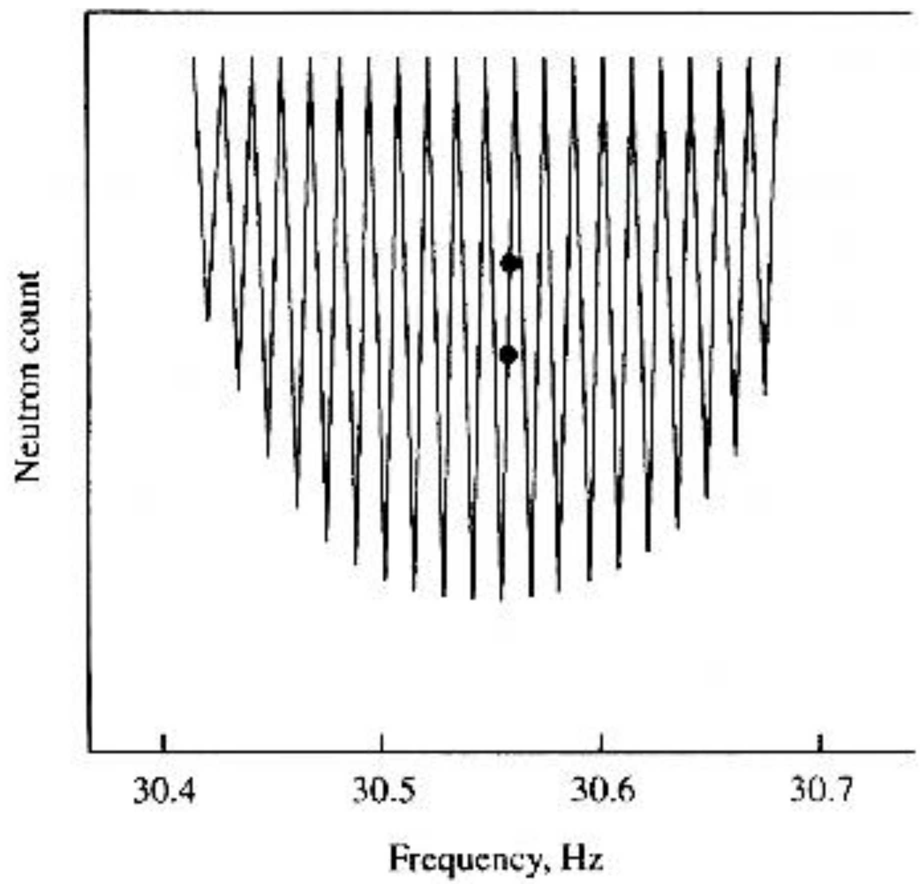
    $\sim 10^{-22}$ e-cm

Experiment: Neutron EDM $< 0.29 \times 10^{-25}$ e-cm

Neutron Electric Dipole Moment



Neutron Electric Dipole Moment



T Violation

TIME REVERSAL (T) INVARIANCE

e electric dipole moment	$<0.87 \times 10^{-28}$ e cm, CL = 90%
μ electric dipole moment	$(-0.1 \pm 0.9) \times 10^{-19}$ e cm
p electric dipole moment	$<0.54 \times 10^{-23}$ e cm
n electric dipole moment	$<0.29 \times 10^{-25}$ e cm, CL = 90%