FISICA NUCLEARE E SUBNUCLEARE I
Corso di laurea Fisica
Lecture 8
(1^{st} part)

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Preliminaries

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Lecture Contents - 1 part

1. The subatomic physics: radioactivity and the discovery of electron (Lecture Ch. 1 and 2)
2. Scattering experiments. Cross section (CDEL Sec. 3.1-3.6)
3. The discovery of the atomic nucleus, the discovery of the proton and the neutron (CDEL Ch. 3.7-3.10)
4. The passage of radiation in matter (CDEL Sec. 4.1-4.9)
5. Particle detectors (CDEL chap. 4.10)
6. Interactions and particles (CDEL Sec. 5.1-5.3)
7. Strong interactions and Yukawa's hypothesis (CDEL Sec. 5.4-5.7)
8. Decay laws. Breit and Wigner formula (CDEL Ch. 5.8-5.10)
9. Cosmic rays and the discovery of the positron (CDEL Sec. 6.1-6.2)
10. Pions and muons (CDEL Sec. 6.3-6.4)

Lecture Contents - 2 part

11. Strange particles (CDEL chap. 6.5)
12. Particle accelerators (CDEL chap. 6.6)
13. The discovery of the antiproton (CDEL chap. 6.7)
14. Neutrinos (CDEL chap. 6.8)
15. The parity. Symmetries C and T (CDEL Sec. 7.1-7.3)
16. Parity violation(CDEL chap. 7.4)
17. Isospin (CDEL chap. 7.5)
18. Hadronic resonances (CDEL chap. 7.6)
19. The quark model (CDEL chap. 7.7)
20. Property of nuclei: the masses and stability (CDEL chap. 8)

Contents

Symmetries and invariances

Symmetries play an important role in particle physics. The mathematical description of symmetries uses group theory.
Symmetry: if a set of transformations, when applied to a system, leaves system unchanged

Symmetries connected with Conservation Laws Noether's Theorem (1917)

- Every continuous symmetry of nature yields a Conservation Law
- Converse is also true: every conservation law reflects an underlying symmetry

Symmetries connected and Conservation Laws

Symmetry		Conservation Law
Translation in time	$\longleftrightarrow$	Energy
Translation in space	$\longleftrightarrow$	Momentum
Spatial Rotation	$\longleftrightarrow$	Angular Momentum
Gauge Transformation (Electrodynamics)	$\longleftrightarrow$	Charge

Figure: Invariance of a system under a transformation and the corresponding conserved quantity

Figure: A.Noether(1882-1935)

Symmetries connected and Conservation Laws: Reminder

In quantum mechanics,any observable quantity corresponds to the expectation value of a Operator, in a in a given quantum state and its time evolution, if the operator does not depend explicitely on time is given by[1]:

$$\frac{\mathsf{d}}{\mathsf{dt}} < Q > = \frac{1}{i\hbar} < [Q, H] > = \frac{1}{i\hbar} < (QH - HQ) >$$

$< Q >=< \psi|Q|\psi >$ expectation value of operartor Q in the state $|\psi>$

An observable quantity, non depending explicitly on time, will be conserved, if and only, if the corresponding quantum operator commutes with the Hamiltonian.

$$\frac{\mathsf{d}}{\mathsf{dt}} < Q > = 0 \text{ if and only if } [Q, H] = 0.$$

[1] see bibliography:CDEL,DF,more complete DG

Symmetries connected and Quantum numbers: Reminder

- In quantum mechanics, when two operators commute, they can be diagonalized simultaneusly,$\Longrightarrow$ a complete set of common eigenfunctions.
- If the Hamiltonian has an underlying symmetry defined by generator Q, the energy eigenstates are also eigenfunctions of operator Q, labelled with quantum numbers corresponding to the eigenvalue of Q.
- **Quantum numbers are conserved in any physical process where the interaction Hamiltonian for some transition (e.g. decay or reaction) is invariant under symmetry transformation.**
- For transition, in which interaction Hamiltonians are not invariant under symmetry transformations, the corresponding quantum numbers do not have to be conserved.

Symmetries

Categories:

1. **Continuous symmetries** .Symmetry transformatios identified with continuous transformations,depend on a continuous set of parameters.
2. **Discrete symmetries** corrispond to some kind of reflections identified with discrete transformations.

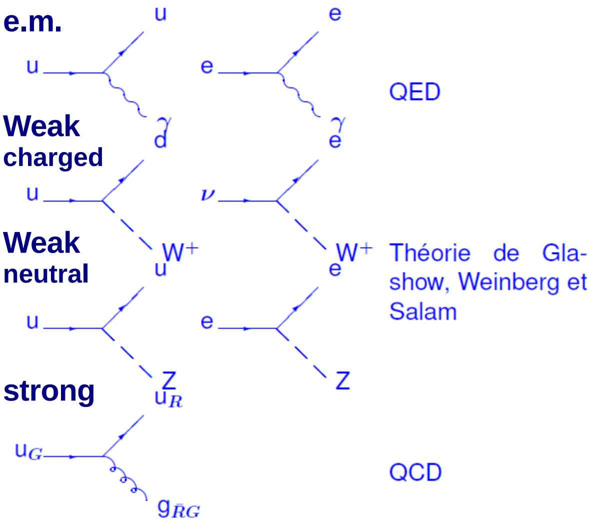
♠ *Example: continous symmetries: space translations* If P (momentum) is the generator of the operator D of space translations. IF H is invariant under transations [D,H] = 0 hence:

$$[P, H] = 0$$

The following three statements are equivalent:

- Momentum is conserved for an isolated system.
- The hamiltonian is invariant under space translations.
- The momentum operator commutes with the hamiltonian.

Forces



e.m.
Weak
charged
Weak
neutral
strong
u
u
γ
d
u
W+
u
u
Z
u_R
u_G
g_R̄G
e
e
γ
e
ν
W+
e
e
Z
QED
Théorie de Glashow, Weinberg et Salam
QCD

Conservation laws

	Strong	E.M.	Weak
Energy/Momentum	√	√	√
Electric Charge	√	√	√
Baryon Number	√	√	√
Lepton Number	√	√	√
Isospin(I)	√	×	×
Strangeness(S)	√	√	×
Charm(C)	√	√	×
Parity(P)	√	√	×
Charge Conjugation(C)	√	√	×
CP (or T)	√	√	×
CPT	√	√	√

Contents

Discrete Symmetries

• The parity, **P**, or space inversion, is a transformation that takes a function from a right handed coordinate frame to a left handed one, or viceversa. A space-time four vector changes:

$$\begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} \xrightarrow{P} \begin{pmatrix} ct \\ -x \\ -y \\ -z \end{pmatrix}$$

The parity operation is distinct from spatial rotations because a left handed coordinate system cannot be obtained from a right handed one through any combination of rotations. The operation of spatial inversion of coordinates is produced by the **parity operator P**:

$$\boxed{\mathbf{P}\psi(\vec{r}) \; = \; \psi(-\vec{r})}$$

Parity

Repetition of this operation implies $P^2 = 1$ so that P is a unitary operator.

$$P\psi(\vec{r}) \xrightarrow{P} \psi(-\vec{r}) \xrightarrow{P} \psi(\vec{r})$$

Therefore if there are parity eigenvalues they must be: $P = \pm 1$.
Examples:

$$P = +1 \quad \psi(x) = \cos\ x \rightarrow P \rightarrow \cos(-x) = \cos x = \psi(x)$$
$$P = -1 \quad \psi(x) = \sin\ x \rightarrow P \rightarrow \sin(-x) = -\sin x = -\psi(x)$$
$$P = ? \quad \psi(x) = \sin\ x + \cos x \rightarrow P \rightarrow = -\sin x + \cos x \neq \pm\psi(x)$$

? undefined parity.

- States of with P = + 1 are even
- States of with P = - 1 are odd
- The parity is a multiplicative operator

Changing under P

The components of position and momentum vectors change under inversion of coordinate , while magnitudes are preserved:

$$\vec{r} \xrightarrow{P} -\vec{r} \quad \text{vector}$$

$$\vec{p} = m\frac{\mathrm{d}\vec{r}}{\mathrm{dt}} \xrightarrow{P} m\frac{\mathrm{d}(-\vec{r})}{\mathrm{dt}} = -\vec{p} \quad \text{vector}$$

$$|\vec{r}| = (\vec{r}\cdot\vec{r})^{\frac{1}{2}} \xrightarrow{P} \left[(-\vec{r})\cdot(-\vec{r})\right] = (\vec{r}\cdot\vec{r})^{\frac{1}{2}} = |\vec{r}| \quad \text{scalar}$$

$$\text{same for momenta}$$

There exist scalar and vector quantities that do not transform under parity as those, they transform opposite the normal vector and scalar.

$$\text{angular momentum}$$

$$\vec{L} = \vec{r}\times\vec{p} \xrightarrow{P} (-\vec{r})\times(-\vec{p}) = \vec{r}\times\vec{p} = \quad \text{axial- vector}^2$$

$$\text{volume of parallelepiped}$$

$$\vec{a}\cdot(\vec{b}\times\vec{c}) \xrightarrow{P} (-\vec{a})\cdot(-\vec{b}\times-\vec{c}) = -\vec{a}\cdot(\vec{b}\times\vec{c}) \quad \text{pseudoscalar}$$

Parity

Quantity Q	$\mathbf{P}$(Q)	Parity
Scalar s	$\mathbf{P}$(s) = s	+1
Pseudoscalar p	$\mathbf{P}$(p) = - p	-1
Vector $\vec{\nu}$	$\mathbf{P}(\vec{\nu})$ = - $\vec{\nu}$	-1
Axialvector $\vec{a}$	$\mathbf{P}(\vec{a})$ = $\vec{a}$	+1

Parity operator

The parity operation P performs a spatial inversion of coordinates through the origin:

$$P\psi(\vec{r}) \;=\; \psi(-\vec{r})$$

parity eigenvalues are $P \;=\; \pm 1$

Parity of particles

The eigenstates of Schrödinger equation for a central potential V(r) are the spherical harmonics $Y_{\ell m}$:

$$\psi_{n\ell m}(\vec{r}) = R_{n\ell}(r) Y_{\ell m}(\theta, \phi)$$

where n, ℓ and m are, respectively, the radial, orbital and projection quantum numbers

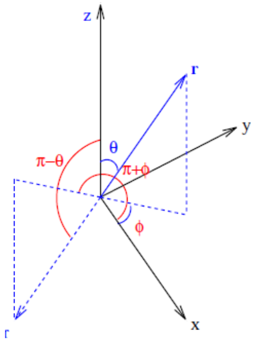
The parity transformation in spherical coordinates:

$$\vec{r} \xrightarrow{P} -\vec{r},$$

$$\theta \xrightarrow{P} \pi - \theta, \phi \xrightarrow{P} \pi + \phi$$

the spherical harmonics behave:

$$Y_{\ell m}(\theta, \phi) \xrightarrow{P} Y_{\ell m}(\pi - \theta, \pi + \phi) = (-1)^{\ell} Y_{\ell m}(\theta, \phi)$$



Parity of particles

Parity transform any wave function that is an eigenstate of orbital angular momentum as

$$\psi_{n\ell m}(\vec{r}) \xrightarrow{P} (-1)^{\ell}\psi_{n\ell m}(\vec{r})$$

- **The parity is a multiplicative operator.**

Example: the hydrogen atom (appendix for better understanding)

Intrinsic parity

- A quantum mechanical wave function can have, **in addition**, an **intrinsic parity** independent of its spatial transformation property and, correspondingly, a general quantum state that is described by eigenfunctions of orbital angular momentum will transform under parity as:

$$\psi_{n\ell m}(\vec{r}) \xrightarrow{P} \eta_\psi (-1)^\ell \psi_{n\ell m}(\vec{r})$$

  η_ψ is the intrinsic parity of quantum state.Of course $\eta_\psi^2 = 1$
- A **total parity of a quantum mechanical state** is:

$$\eta_{TOT} = \eta_\psi (-1)^\ell$$

Intrinsic parity

- Thus, parity conservation law requires the assignment of an intrinsic parity to each particle.
- Protons and neutrons are conventionally assigned positive parity

$$P_p = P_n = +1$$

- The assignment of an intrinsic parity is meaningful when particles interact one another (as in the case of electric charge).
- The nucleon intrinsic parity is a matter of convention.
- The relative parity of particle and antiparticle is not a matter of convention
- Fermions and antifermions are created in pairs, whereas this is not the case for bosons.
- Fermions: particle and antiparticle have opposite parity.
- Bosons: particle and antiparticle have equal parity.

Example: Intrinsic parity of fermions and photon

- The intrinsic parity of fermions is P = even
- The intrinsic parity of antifermions is P = odd
- Parity is a multiplicative quantum number, so the parity of a many particle system is equal to the product of the intrinsic parities of the particles times the parity of the spatial wavefunction which is $(-1)^L$. As an example, positronium is an e^+e^- system with:

  $$P(e^+e^-) = P_{e^-}P_{e^+}(-1)^L = (-1)^{L+1}$$

  where L is the relative orbital angular momentum between the e^+ and e^- .
- The photon γ is represented by the vector potential A^μ, a vector then its parity is P_γ = -1.

Parity Conservation

Parity Conservation and violation

Parity is conserved in strong and electromagnetic interactions, whereas it is **violated in weak interactions**.

Charge Coniugation

• Charge Conjugation,**C**, is a discrete symmetry that reverses all the additive quantum numbers as the electrical charge, baryon and lepton numbers and the flavor charges, but it does not change the mass, linear momentum or spin of a particle.

- Like the parity operator it satisfies $C^2 = 1$, and has possible eigenvalues $C = \pm 1$. Electromagnetism is C invariant, since Maxwell's equations apply equally to + and - charges.

$$q \xrightarrow{C} -q \quad \vec{j} \xrightarrow{C} -\vec{j} \quad \vec{E} \xrightarrow{C} -\vec{E} \quad \vec{H} \xrightarrow{C} -\vec{H}$$

- However the electromagnetic fields change sign under C $\Longrightarrow C_\gamma = -1$.
- The classification of the electron as particle and positron as antiparticle is arbitrary.The definition of positive and negative electric charge, positive and negative strangeness, the assignment of baryon number, etc., are all a matter of convention.
- Once a choice is made, however, we can measure the quantum numbers of other particles relative to the defined assignments.

Charge Coniugation

The charge conjugation operation inverts all internal quantum numbers of states, and thereby relates particles to their antiparticles.

particle $\Longleftrightarrow$ antiparticle

	p	$\xrightarrow{C}$	$\bar{p}$
Q	$+e$		$-e$
B	+1		-1
μ	$+2.79(e\hbar/2mc)$		$-2.79(e\hbar/2mc)$
σ	$\frac{1}{2}\hbar$		$\frac{1}{2}\hbar$

Charge Coniugation

- A state can be an eigenstate of the charge conjugation operartor C,if, at least, is electrically neutral. γ,π^0 can be C eigenstate.
- Not all charge-neutral states are eigenstates of C, since they may carry other internal quantum number. This are not C eigenstate $|n>\xrightarrow{C}|\bar{n}>$ $|K^0>\xrightarrow{C}|\bar{K^0}>$
- For fermions charge conjugation changes a particle into an antiparticle, so fermions themselves are not eigenstates of C . Combinations of fermions can be eigenstates of C .

Charge Coniugation

Charge Conjugation is a discrete symmetry that reverses all the additive quantum numbers as the electrical charge, baryon and lepton numbers and the flavor charges
Charge Coniugation eigenvalues are $C = \pm 1$

Charge Conjugation Conservation

- Since electric charge is the source of electric and magnetic fields:

$$\vec{E} \xrightarrow{C} -\vec{E}$$

$$\vec{B} \xrightarrow{C} -\vec{B}$$

- Both $\vec{E}$, $\vec{B}$ are linear in electric charge. Maxwell equations are invariant under C transformation.
- The γ, the quantum of electromagnetic field, must have $\eta_c(\gamma) = 1$.
- If the charge conjugation is symmetry of theory [H,C]$= 0 \Longrightarrow$ C charge parity must be conserved.
- Determination of the charge parity of π^0:

$$\pi^0 \rightarrow \gamma \ + \ \gamma$$

$$\eta^c(\pi^0) \ = \ \eta^c(\gamma) \ \times \ \eta^c(\gamma) \ = \ (-1)^2 \ = \ 1$$

$\rightarrow$ π^0 must be even under C. .

Charge Conjugation Conservation

Charge conjugation Conservation and violation

Charge conjugation C is conserved in strong and electromagnetic interactions, but **not in weak interactions**.

Time Reversal

• Time reversal **T** (t) = (-t), is another discrete symmetry operator with $T^2 = 1$, and possible eigenvalues $T = \pm 1$. The solutions of the Dirac equation describe antifermion states as equivalent to fermion states with the time and space coordinates reversed.

$$t \xrightarrow{T} -t$$

$$\vec{r} \xrightarrow{T} \vec{r}$$

$$\vec{p} = m\frac{\mathrm{d}\vec{r}}{\mathrm{dt}} \xrightarrow{T} m\frac{\mathrm{d}(\vec{r})}{\mathrm{d}-\mathrm{t}} = -\vec{p}$$

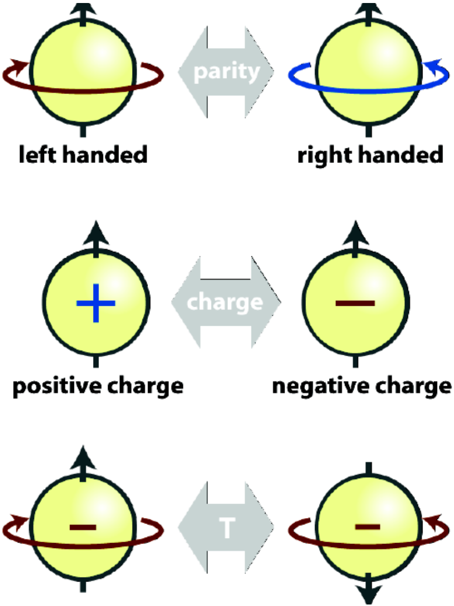
$$\vec{L} = \vec{r} \times \vec{p} \xrightarrow{T} \vec{r} \times -\vec{p} = -\vec{L}$$

The spin changes as angular momentum.

• The Schrödinger equation under T see Appendix[3]

[3] see bibliography more complete DG

CPT actions



parity
left handed
right handed
charge
positive charge
negative charge
T

Summary of Discrete Symetry Transformation

Quantity	Notation	P	C	T
Position	$\vec{r}$	-1	+1	+1
Momentum(Vector)	$\vec{p}$	-1	+1	-1
Spin(Axial Vector)	$\vec{\sigma} = \vec{r} \times \vec{p}$	+1	+1	-1
Helicity	$\vec{\sigma} = \vec{\sigma} \cdot \vec{p}$	-1	+1	+1
Electric Field	$\vec{E}$	-1	-1	+1
Magnetic Field	$\vec{B}$	+1	-1	-1
Magnetic Dipole Moment	$\vec{\sigma} \cdot \vec{B}$	+1	-1	+1
Electric Dipole Moment	$\vec{\sigma} \cdot \vec{E}$	-1	-1	-1
Transverse Polarization	$\vec{\sigma} \cdot (\vec{P_1} \times \vec{P_2})$	+1	+1	-1

CP and CPT actions

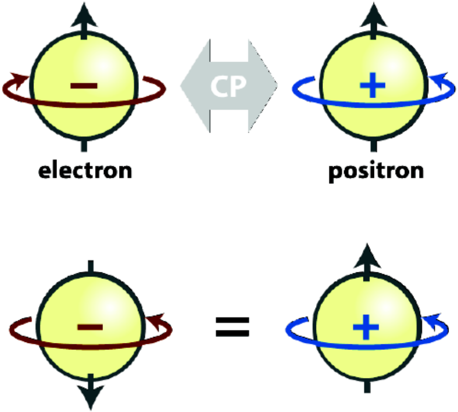


Figure: Action of CP(top) and CPT(bottom) operators on fundamential fermions.Equal sign in the bottom plot represents CPT conservation.

Contents

Parity violation

- Two decay modes of the charged kaons, (now) $K^+ \rightarrow \pi^+ \ + \ \pi^0$ $K^+ \rightarrow \pi^+ \ + \ \pi^+ \ + \ \pi^-$ in the 1950's.

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- Difference: Parity.

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  i.e. can distinguish between left- and right-handed coordinate systems. This is not the case for strong or electromagnetic interactions.
- The experiment that showed conclusively that parity is violated in weak interactions involved in the β decays of ^{60}Co

β decay of cobalt

First test of this hypothesis: β-decay of cobalt, performed by C.S.Wu (Madame Wu) and E.Ambler in 1956.

- Idea: Observe some spatial asymmetry in:

  $$^{60}Co \rightarrow ^{60}Ni + e^- + \bar{\nu}_e$$

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- Give some reference direction in space, add some magnetic field to align the spin of the cooled cobalt nuclei.
- Measure the emission of the electrons against or with the spin direction of the nuclei and construct asymmetry.
- Neither spin nor the magnetic field change under mirror reflections (they are axial vectors - like cross products), but momentum does.

Cobalto 60 decays

$$\boxed{{}^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e}$$

${}^{60}Co$(J=5) decays to ${}^{60}Ni^*$(J=4) transition.

- ${}^{60}Co \xrightarrow{n \rightarrow p^+ e^- \bar{\nu}_e} {}^{60}Ni^*$
- ${}^{60}Co$ has 33 n and 27 p
  ${}^{60}Ni^*$ has 32n and 28 p

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- Key points in design of experimental set-up:
  1. **degree of ${}^{60}Co$ alignment in external $\vec{H}$** determined from observation of ${}^{60}Ni^*$ γ-rays.
  2. $\vec{p}$ **momentum of emitted electrons**

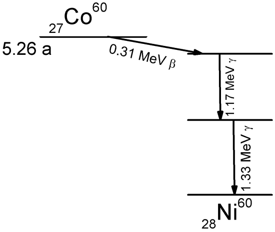
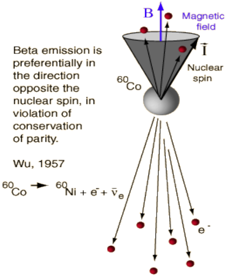


Figure: ${}^{60}Co \rightarrow {}^{60}Ni$ transition .

Cobalto 60 experiment



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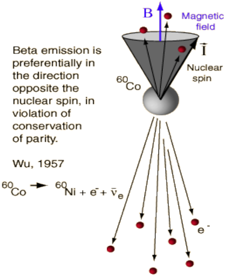

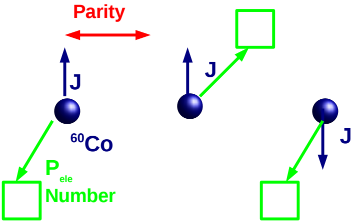

Detector

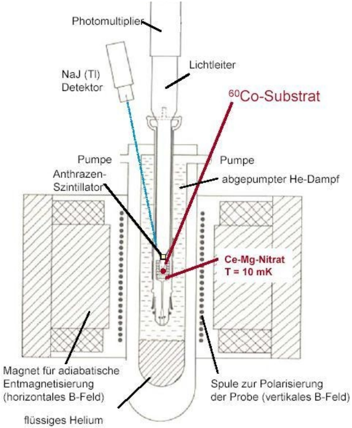

Figure: Schematic drawing of the cryostat and magnet.

Detector

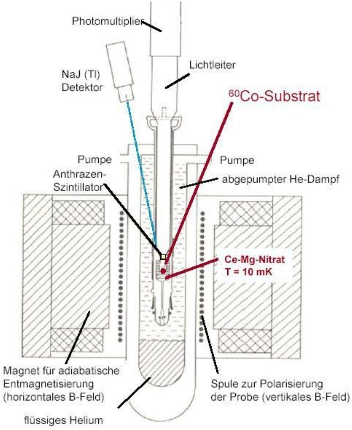

Figure: Schematic drawing of the cryostat and magnet.

- A sample of ${}^{60}Co$ at 0.01 K inside a solenoid. At this temperature a high portion of ${}^{60}Co$ nuclei are aligned by applying a strong external field.

Detector

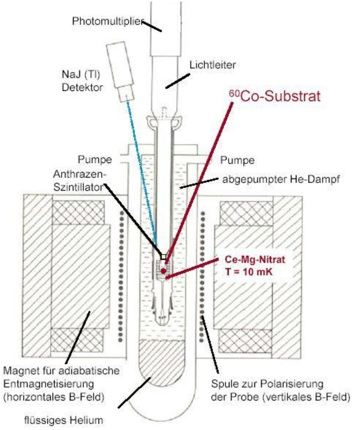

Figure: Schematic drawing of the cryostat and magnet.

- A sample of ^{60}Co at 0.01 K inside a solenoid. At this temperature a high portion of ^{60}Co nuclei are aligned by applying a strong external field.
- The degree of ^{60}Co alignment could be determined from observation of angular distribution of γ-rays from ^{60}Ni

Detector

- Beta particles from ^{60}Co decay were detected by a thin anthracene crystal (scintillator) placed above the ^{60}Co source. Scintillations were transmitted to the photomultiplier tube (PMT) on top of the cryostat

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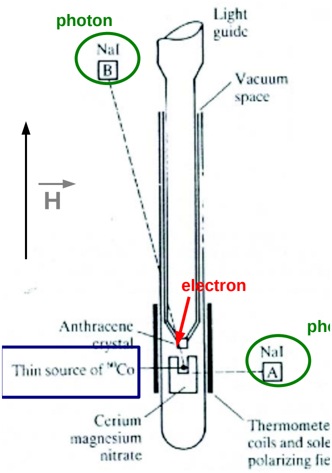

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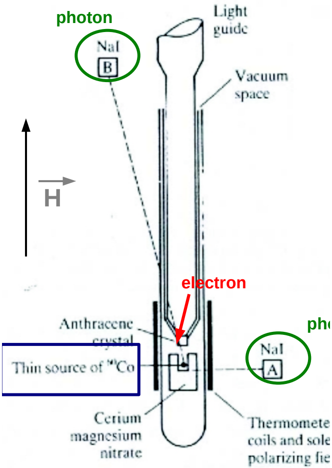

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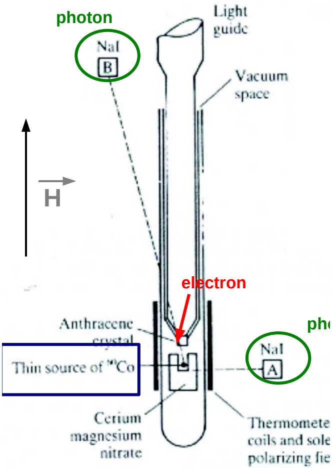

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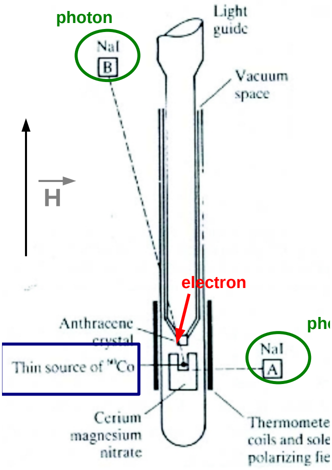


- The angular distribution of emitted electrons $<\theta>$ was measured relative to the $\vec{H}$ direction.
- The electrons were emitted preferentially in a direction opposite of $\vec{H}$, therefore opposite to spin($\vec{J}$) of ^{60}Co nuclei.
- To perform the measure at different $<\theta>$ the two $\vec{H}$ orientations used

Detector

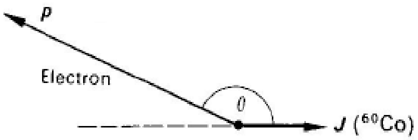


Figure: Kinematics

If **parity is conserved**:

$$< \cos\theta > \propto < \vec{J} \cdot \vec{p} > = 0$$

- **equal probability for the electrons to be emitted $\cos < 0$** and for **$\cos > 0$**.

- $\vec{J}$ = spin of ^{60}Co nucleus
- $\vec{p}$ = electron momentum
- $\cos < \theta >$,expectation value was finite and negative

$$< \cos\theta > = < \frac{\vec{J} \cdot \vec{p}}{|\vec{J}||\vec{p}|} >$$

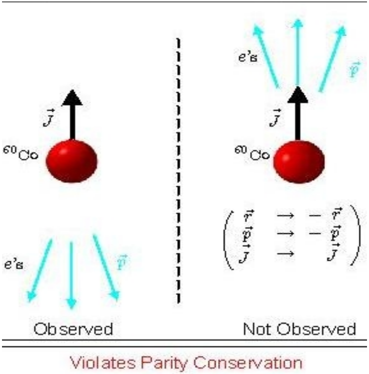
$$= \xrightarrow{P} < \frac{\vec{J} \cdot -\vec{p}}{|\vec{J}||\vec{p}|} > =$$

$$= - < \frac{\vec{J} \cdot \vec{p}}{|\vec{J}||\vec{p}|} >$$

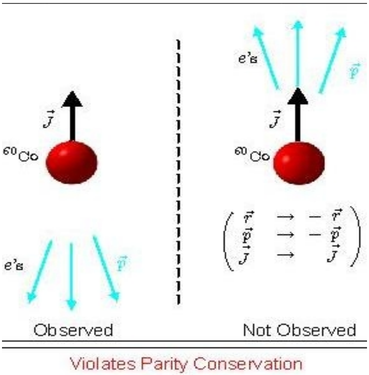
$$= - < \cos\theta >$$

- if right and left coordinate are physically equivalent the observed value in two frames should be identical.

Parity violation



Parity violation



If parity is conserved:

$$< \cos\theta > = \; - < \cos\theta >$$

♠Electrons must be emitted with an equal probability in both directions.

Results

- Graphs:
  - top -γ anisotropy,
    counting rate , control of
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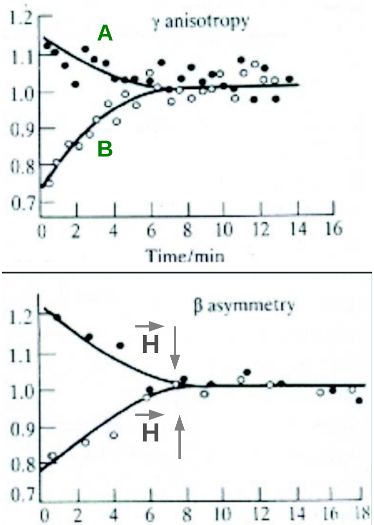
Results

- Graphs:
  - top -γ anisotropy, counting rate , control of polarisation;
  - bottom - asymmetry - counting rate in the anthracene crystal relative the rate without polarisation (after the set up was warmed up) for two orientations of magnetic field.



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- **Beta asymmetry - Parity not conserved**

Contents

CPT theorem

- The discrete symmetries,P,T and C appear violated in some processes.
- The CP T theorem requires that all interactions that are described by localized Lorentz invariant gauge theories must be invariant under the combined operation of C , P and T in any order. The proof of the CP T theorem is based on very general field theoretic assumptions. It can be thought of as a statement about the invariance of Feynman diagrams under particle/antiparticle interchange, and interchange of the initial and final states.
- The CP T theorem also means that the transformation properties of gauge theories under the discrete symmetries C , P and T are related to each other:

$$CP \Longleftrightarrow T \quad CT \Longleftrightarrow P \quad PT \Longleftrightarrow C$$

The first of these establishes that time reversal invariance is equivalent to CP invariance.

CPT theorem consequences

1. Bose-Eistein particles(integer-spin), Fermi-Dirac(half-integer spin). An operator with integer spin is quantized using commutation relations, and an operator with half-integer spin is quantized using anticommutationrelation.
2. Particle and anti-particles have identical masses and same total lifetimes
3. All the internal quantum numbers of antiparticles are opposite to those of their partner particles.

The CPT theorem is consitent with all known observations and CPT appeard to be a true symmetry of all interactions.

Appendix: Parity

Example: The hydrogen atom

Example of Parity:

$$\psi(r,\theta,\phi) = \chi(r)Y_\ell(\theta,\phi)P_m^\ell(\cos\theta)e^{im\phi}$$

$$\psi(r,\theta,\phi) = \chi(r)\sqrt{\frac{(2\ell + 1)(\ell - m)!}{4\pi(\ell + m)!}}\,P_m^\ell(\cos\theta)e^{im\phi}$$

$$\vec{r} \xrightarrow{P} -\vec{r}, \theta \xrightarrow{P} \pi - \theta, \phi \xrightarrow{P} \pi + \phi$$

$$e^{im\phi} \xrightarrow{P} e^{im(\phi + \pi)} = (-1)^m e^{im\phi}$$

$$P_m^\ell(\cos\theta) \xrightarrow{P} (-1)^{(\ell + m)} P_m^\ell(\cos\theta)$$

$$Y_{\ell m}(\theta,\phi) \xrightarrow{P} Y_{\ell m}(\pi - \theta, \pi + \phi) = (-1)^\ell Y_{\ell m}(\theta,\phi)$$

Appendix: Time reversal

Note on The Schrödinger equation.

• The Schrödinger equation $i\hbar\frac{\partial\phi}{\partial t} = H\psi$,is a first-order equation in the time derivative, it **cannot be invariant under T** as symple:

$$\psi(\vec{r},t) \xrightarrow{T} \psi(\vec{r},-t)$$

if require that the wave function to transform under time reversal: $\psi(\vec{r},t) \xrightarrow{T} \psi^*(\vec{r},-t)$ If H is real for the complex cojugate $i\hbar\frac{\partial\phi}{\partial t} = H\psi$ then $t \to -t$ $i\hbar\frac{\partial\phi*}{\partial t} = H\psi^*$.

• The Schrödinger equation can be invariant under T if ϕ and ψ^* obbey to same equation.