Introduction to particle physics
Lecture 12: Weak interactions

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Outline

1. Gauge theory of weak interactions
2. Spontaneous symmetry breaking
3. Generation structure of fermions
4. More on weak interactions

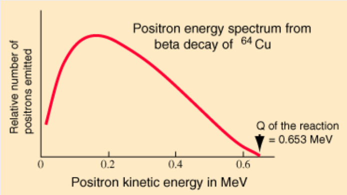
Gauge theory of weak interactions

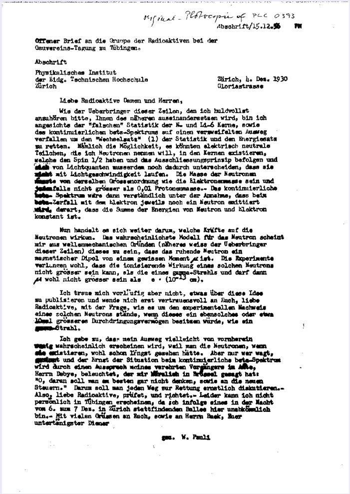
General structure

- As before, want to copy the success of QED/QCD:
  - Introduce conserved charges through global phase invariance
  - In QED: Write electron field ψ, attach charge $q_e = -1$
  - In QCD: Write quark field Ψ_q as colour triplet $(\psi_q^{(r)}, \psi_q^{(g)}, \psi_q^{(b)})$
  - Promote global phase invariance to local phase invariance
  - Introduce "gauge fields" to ensure the invariance
  - Free fields ψ get coupled with "gauge fields " A, the A must be massless to preserve gauge invariance (See lecture 9.)
  - Effect of gauge fields in QCD: $\psi_q^{(r)} \xrightarrow{A^{r\bar{b}}} \psi_q^{(g)}$
    $\Longrightarrow$ gluons carry a "charge" (a colour and an anti-colour)
- In QED/QCD interaction does not change "type" of particle if possible, only charge quantum number gets changed.
- In contrast: Weak interactions trigger β-decays ($n \to p$ or $d \to u$) Must embed this in a "gauge structure", putting different particle species in one multiplet, with charges.

Aside: Neutrinos

- Hypothesised by Pauli 1930: Famous letter to the "Dear radioactive ladies and gentlemen" (see left).
- Reason: In β-decay only two particles seen, but continuous energy spectrum of the electron. Impossible in two-body decays.





Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

A simplified model (for β-decay)

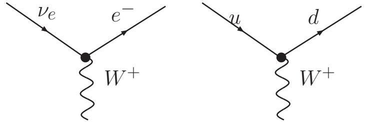
- Weak interactions base on transitions $e^- \longrightarrow \nu_e$, $d \longrightarrow u$ and similar.
- Natural to group the leptons and quarks into

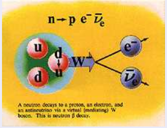
  $$\text{weak iso-doublets } l_e = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix},\ l_q = \begin{pmatrix} u \\ d \end{pmatrix}$$

  each with isospin $|\frac{1}{2}, \pm\frac{1}{2}\rangle$ for upper/lower entries.
- Define weak isospin, make Lagrangian globally phase invariant, promote to local phase invariance and introduce corresponding gauge fields $\vec{W} = W^{+,-,0}$
- Gauge fields carry isospin, namely $W\pm: \ |1, \pm 1\rangle$ and $W^0: \ |1, 0\rangle$.
- Note: Charged weak interactions change flavour, neutral ones don't Other quantum numbers (colour!) is not altered.
- Note also: Reality more complicated (see later).
- Question: How do strange quarks/muons/... fit into that?

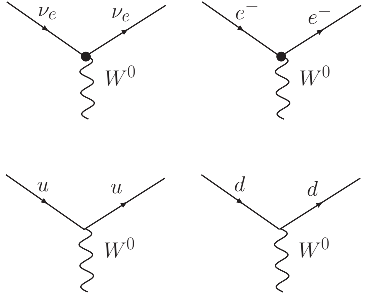
Naive Feynman rules in weak interactions

- Charged interactions (W^+ goes "down", similar for charge-conjugated):





- Neutral interactions (similar for other leptons and quarks):



Problems of weak gauge theory (when invented)

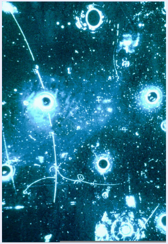
- While charged weak interactions (of the $e^- \rightarrow \nu_e$-type) have been known since 60's, evidence for neutral ones came in 1973 only.
- Local gauge invariance dictates massless gauge bosons (like in QED) but experimental evidence showed that they are in fact very massive:

$$m_W \approx 80.4 \text{ GeV}, \; m_Z \approx 91.2 \text{ GeV}.$$

- Also: note that we'vem oved from W^0 to Z^0 ...

Neutral currents

- Gargamelle at CERN (1973): first "photo" of a "neutral current" event.
- Neutrinos interact with matter in a 1200 litre bubble chamber. Here: A neutrino interacts with an electron (the horizontal line) and evades unseen.

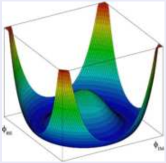


Spontaneous symmetry breaking

Basic idea

- Common phenomenon: Asymmetric solutions to symmetric theory.
- Example: Magnet (e.g. Heisenberg/Ising model).
  Theory: local spin-spin interactions with preference for alignment, but direction not fixed. Nevertheless: Preferred direction emerges. Symmetric state (no alignment) is not state of minimal energy.
- In QFT: Every particle related to a field.
  Ground state of the field (a.k.a. "vacuum") is state of minimal energy and no particles are present. For most fields, minimal energy equals 0, but cases can be constructed, where $E_{\min} = \langle E_0 \rangle = v < 0$.
- Add such a field with $\langle E_0 \rangle = v < 0$ and couple to gauge bosons.
  Can show that v sets scale for mass of gauge bosons.

The Higgs mechanism: Making the gauge bosons massive



- Add a complex iso-doublet Φ to the theory.

  (Iso-doublet to trigger interactions with $\vec{W}$.)

- Lagrangian invariant under $SU(2)$:
  $$\mathbf{G}^{SU(2)_W}\mathcal{L}(\vec{W},\Phi) \rightarrow \mathcal{L}(\vec{W}',\Phi')$$
- Give it a potential of the form $\mu^2|\Phi|^2 + \lambda|\Phi|^4$ $\Longrightarrow$ non-trivial minimum at $|\Phi|^2 = v^2$.
- Picture to the left: Same for real scalars.
- Pick a vacuum, for instance $\mathcal{R}(\Phi_1)_0 = v$.
- Expand in new fields around this vacuum: Three orbital modes parallel to the minimum (the Goldstone modes $\vec{\theta}$), one radial mode (the Higgs field η), which “feels” the potential.
- The Lagrangian is not trivially $SU(2)$ invariant any longer!

  The original symmetry has been hidden by the choice of a ground state - an orientation of v. This is similar to the magnet example above, where at low temperatures the magnetisation introduces a random direction.

The Higgs mechanism: Making the gauge bosons massive

- Absorb the three Goldstone bosons $\vec{\theta}$ into the gauge bosons (by "choosing a gauge"), gives their 3rd polarisation d.o.f.
  $\Longrightarrow$ gauge bosons become massive!

  (Massless spin-1 bosons have two polarisation directions.)

- Note: The neutral Goldstone boson is absorbed by a combination of the original $U(1)$ gauge boson ("B") and W^0, yields a massive Z^0.
  The orthogonal linear combination becomes the photon.
  That's why electroweak symmetry breaking (EWSB) is

$$SU(2)_L \otimes U(1)_Y \xrightarrow{EWSB} U(1)_{e.m.}$$

- One real scalar η ("Higgs boson") remains, interactions fixed.
- This mechanism fixes the interplay of gauge boson masses and their interactions with the mass of the Higgs boson and its interactions
  Testable non-trivial predictions ("Holy grail")
- Note: The Higgs boson also gives mass to the fermions - an even more complicated story, again with keyword "gauge invariance".

Generation structure of fermions

Lepton number

- A simple question: Are the neutrinos emitted in neutron β-decay the same as those emitted in proton β-decay?
- Compare β decays of n and p: $n \to p + e^- + \nu$ and $p \to n + e^+ + \nu$. Suggests that in the former case an anti-neutrino $\bar{\nu}$ is emitted.

  (By moving a particle from left to right, need to "bar" it - replace with antiparticle.)
- This allows to formulate a law lepton-number conservation: Assigning a lepton number of $+1$ to electron, muons and neutrinos, and of -1 to their anti-particles, i.e. positrons, anti-muons and anti-neutrinos, and a lepton number of 0 to all other particles, then in any reaction lepton number is conserved.
- Examples:
  - $\bar{\nu} + p \to e^+ + n$ is allowed
  - $\bar{\nu} + n \to e^- + p$ is forbidden.

The absence of $\mu \longrightarrow e\gamma$

- Further: How do muons, strange quarks etc. fit into the picture?
- Naively, reactions of the type $\mu^- \to e^- + \gamma$ would be allowed:
  A Feynman diagram related to this would look like the muon decaying into a neutrino plus a charged W-boson, which recombine to form an electron, emitting a photon on the way.
  This process has never been observed - experimentally, its (probability to happen) branching ratio $\mathcal{BR} < 10^{-14}$.
- Solution to this puzzle: Postulate two types of neutrinos such that the corresponding doublets read

$$\bar{\Psi}_e = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \text{ and } \bar{\Psi}_e = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}.$$

- Lepton-number conservation $\longrightarrow$ lepton-type number conservation:
  - electron number $= +1$ for e^- and ν_e, $= -1$ for e^+ and $\bar{\nu}_e$, and $= 0$ for all other particles
  - similar for muon number (and tau number, see later).

Genius experimenting: The two-neutrino experiment

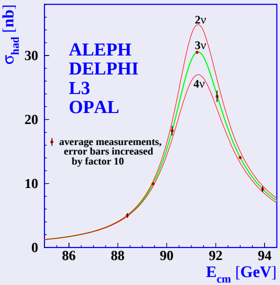
- The main problem when experimenting with neutrinos is to produce them in large quantities. One option, at low energies, is by using the huge fluxes coming from nuclear reactors (electron neutrinos). At large energies, accelerators must be used.
- To this end, for instance, high-energy protons are collided with a beryllium target, producing large numbers of, e.g. pions. They in turn decay into muons and muon-neutrinos. The latter can be isolated by large amounts of material - iron. If there was only one neutrino species, the remaining neutrinos in the experiment could, in principle, initiate two kinds of reactions with equal likelihood, namely

$$\nu + n \longrightarrow \mu^- + p \text{ and } \nu + n \longrightarrow e^- + p.$$

- However, in the first experiment of this kind L.Lederman, M.Schwartz and J.Steinberger used 25 years of accelerator time, producing around 10^{14} neutrinos yielding 51 muons and no electrons, establishing the existence of two kinds of neutrinos.

The number of generations

- Found lepton "generations "
  $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$
- ... quark generations:
  $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$
- Heavier copies of the same underlying structure.



- Note in passing: weak interactions do not mediate between different lepton families (no transition $\mu^- \to \nu_e$ and similar) but mediate between quarks (transitions $s \to u$, $c \to d$, ... exists).
- But: how many generations exist?
- Answer: Three (with light neutrinos)
  The width (lifetime) of Z bosons suggests the existence of three neutrinos species available as decay products.

More on weak interactions

Parity violation: Decays of charged kaons

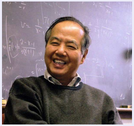
- Two decay modes of the charged kaons massively different. Thus, two different particles assumed in the 1950's:

$$\tau^+ \to \pi^+ + \pi^+ + \pi^- \text{ and } \theta^+ \to \pi^+ + \pi^0.$$

  Lifetime in both modes: $\tau \approx 10^{-8}$ s; therefore a weak decay.

- Difference: Parity.

  Reasoning: Two- and three-pion final states have different parities, if both in *s*-wave. Therefore either the decaying particle(s) have different parities or the interaction responsible must violate parity!

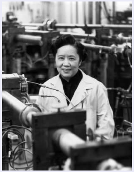


- T.D.Lee and C.N.Yang postulate (1956):

  Weak interactions violate parity,

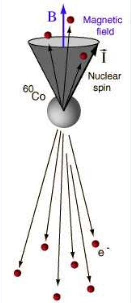
  i.e. can distinguish between left- and right-handed coordinate systems. This is not the case for strong or electromagnetic interactions.

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

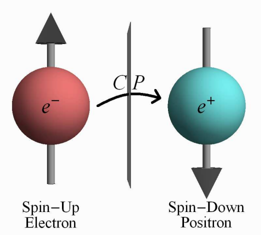
$$^{60}\mathrm{Co} \rightarrow ^{60}\mathrm{Ni} + e^- + \bar{\nu}.$$



- 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.

Handedness and CP-invariance

- In principle this allows to distinguish left- and right-handed coordinate systems and to communicate (e.g. to an alien) which one we're using.
- However, repeating a defining experiment like the cobalt one in an antimatter world, the additional effect of the matter-antimatter symmetry kicks in. It is interesting to note that the weak interaction also violates $\hat{C}$, in such a way that invariance under the product $\hat{C}\hat{P}$ is preserved to a very high degree.



- Weak interactions trigger $\hat{C}\hat{P}$ violation

(Important for matter-antimatter asymmetry in universe, but not enough $\hat{C}\hat{P}$ violation in Standard Model.)

- Its existence is intimately related to ≥ 3 generations of quarks.

Spin, helicity and chirality

- Need a better understanding of $\mathcal{P}$-violation.
- Reminder: Fermions can be described by two components. At low velocities they can be interpreted as the different spin states.
- For large velocities, spins w.r.t. a given external axis are not so useful any more. Therefore define spin w.r.t. the axis of motion: helicity. But this is not invariant under Lorentz transformations (simple argument: boost particle in its rest frame).
- Alternatively, use the fermion's chirality (or handedness).
- Both helicity and chirality flip under parity. In fact, the definitions exactly coincide for massless fermions.

Experimental check: Electron polarisation in β-decays

- $\mathcal{P}$ violation induces an asymmetry in the e^--direction in β decay.
- It also affects the helicities of the electrons. With $\hat{P}$ conserved as many plus as minus helicity electrons are emitted.
- Defining a polarisation

$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

  $P = \pm 1$ translates into all electrons being helicity ± 1. Therefore, if all electrons are left-handed, $P = -v/c$.
- Experimentally: all electrons emitted in β-decay are left-handed.

Neutrino helicity

- This finding constrains the coupling structure very tightly.
- Assuming that the structure of the weak interaction is universal for all fermions, this implies that only left-handed fermions and right-handed anti-fermions take part in weak interactions.
- Since the neutrinos interact only through the weak interaction (and through gravity, to be precise), only left-handed neutrinos seen.
- To verify this, a simple β-decay can be used.
- The first experiment of this kind was done by M.Goldhaber and collaborators. It is considered to be one of the most clever experiments in the history of particle physics (see next slide).
- Similar experiments have been done, e.g. with the decays of $\pi^+ \rightarrow \mu^+ + \nu_\mu$. Since the π^+ is a spin-0 particle, the spins of the muon and the neutrino must always be opposite. Measuring the muon spin (helicity) therefore allows to deduce the neutrino helicity.

The Goldhaber experiment (1958)

- Use the inverse β-decay of the spin-0 nucleus $^{152}\mathrm{Eu}$:
    - the electron is captured (instead of being emitted) producing an excited (spin-1) $^{152}\mathrm{SM}$ nucleus, emitting a neutrino.
    - the nucleus decays then into its spin-0 ground state and a photon.

$$e^- +^{152}\mathrm{Eu}(J=0) \rightarrow \left[^{152}\mathrm{SM}(J=1) \rightarrow^{152}\mathrm{SM}(J=0)+\gamma\right]+\nu$$

- Due to the masses of the involved particles, the nucleus remains at rest and the neutrino and the photon are emitted back-to-back, with angular momentum-0.
- Because of the nucleus before and after being spin-0, their spins must be opposite and add up to the electron spin.
- In order to measure the photon helicity, magnetic material is used. Depending on the photons' helicity, they are either absorbed by the material or not. Thus, controlling the magnetic material allows to "dial" the photon helicity.

Summary

- Introduced the gauge theory of weak interactions:
  bases on doublets containing only left-handed fermions of different type.
- Generation/family structure of fermions
- Weak interactions conserve lepton- and lepton-family number, also conserve quark number, but not quark-family number.
- Introduce electroweak symmetry breaking: Higgs mechanism: A subtle way of beating "symmetry enforces massless bosons"
- Discussed discrete symmetries in weak interactions.