Foundations of Physics III
Quantum and Particle Physics
Lecture 11

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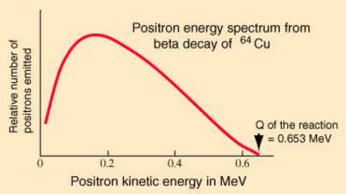
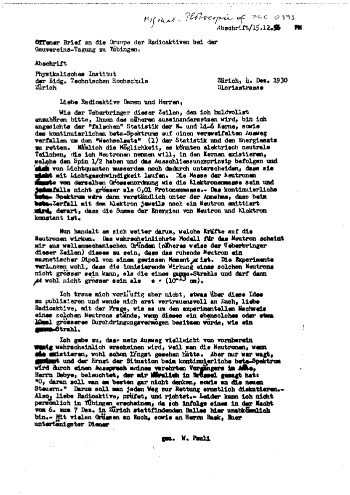
February 24, 2012

The "invention" of 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.





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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

Gauge theory of weak interactions

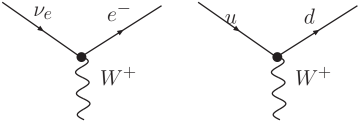
- As before, want to copy the success of QED/QCD:
  - Introduce **conserved charges** through **global phase invariance**
  - In QED: Write electron field ψ, attach charge $q_e = -1$
  - In QCD: Write quark field Ψ_q as colour triplet $(\psi_q^{(r)}, \psi_q^{(g)}, \psi_q^{(b)})$
  - Promote global phase 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 10.)
  - Effect of gauge fields in QCD: $\psi_q^{(r)} \xrightarrow{A^{r\bar{g}}} \psi_q^{(g)}$
    $\Longrightarrow$ 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.

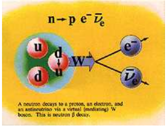
A simplified model (for β-decay)

- Todays knowledge: weak interactions incorporate transitions $e^- \to \nu_e$, $d \to u$ ... (different from QED and QCD!).
- Natural to group the leptons and quarks into
$$\textbf{weak iso-doublets } l_e = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix},\ l_q = \begin{pmatrix} u \\ d \end{pmatrix}$$
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 $\vec{W} = W^{+,-,0}$ – one for each Pauli matrix.
- 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.

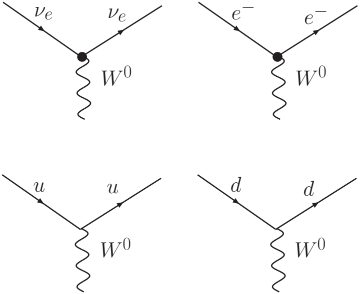
Naive Feynman rules in weak interactions

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





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



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, fairly long; therefore assumed (correctly) to be weak decays.

- 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 - weak interactions are very different here!

Experimental check: Electron polarisation in β-decays

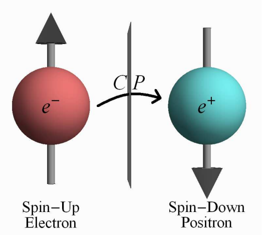
- $\mathcal{P}$ violation induces an asymmetry in the e^--direction in β decay.
- It also affects the helicities of the electrons. With $\hat{P}$ conserved as many plus as minus helicity electrons would be emitted.
- Defining a polarisation

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

  $P = \pm 1$ 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**.
- Therefore: Only left-handed components of fermions take part in weak interactions. Neutrinos are completely left-handed in the Standard Model.

Handedness and CP-invariance

- This allows to establish the notion of left- and right-handed coordinate systems and to communicate **on physical grounds** which one is used.
- However, repeating a parity violation experiment 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

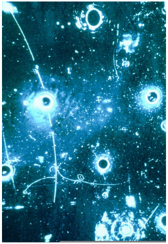
(Important for matter-antimatter asymmetry in universe, but not enough $\hat{C}\hat{P}$ violation in Standard Model.)

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

Problems of weak gauge theory (when invented)

- While charged weak interactions (of the $e^- \to \nu_e$-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've moved from W^0 to Z^0 ...

- 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 $E_{\rm min} = \langle E_0\rangle = v < 0$.
- 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

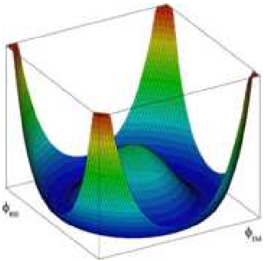
- Add a complex iso-doublet Φ to the theory.

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

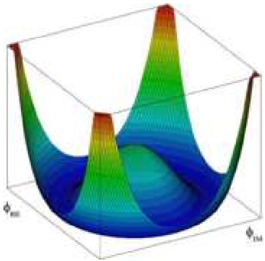
- Lagrangian invariant under $SU(2)$:

  $$\mathbf{G}^{SU(2)_W}\mathcal{L}(\vec{W},\Phi) \to \mathcal{L}(\vec{W}',\Phi')$$

- Give it a potential of the form $\mu^2|\Phi|^2 + \lambda|\Phi|^4$ $\Longrightarrow$ non-trivial minimum at $|\Phi|^2 = v^2 = -\frac{\mu^2}{\lambda}$.
- Picture to the right: Sketch for real rather than complex 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.



- 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.)
- One real scalar η ("Higgs boson") remains, interactions fixed.
- This mechanism fixes the interplay of gauge boson masses and their interactions with the Higgs boson (proportional to their mass!).

  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".

- 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, γ.

$$\begin{aligned} Z^0 &= \cos\theta_W W^0 - \sin\theta_W B^0 \\ \gamma &= \sin\theta_W W^0 + \cos\theta_W B^0 \,. \end{aligned}$$

  The mixing angle is known as the Weinberg angle, and $\sin\theta_W \approx 0.23$. The weak coupling is related to the electromagnetic one by $g_W = e/\sin\theta_W$.

- That's why electroweak symmetry breaking (EWSB) is

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

Learning outcomes

- Introduced the gauge theory of weak interactions:
  bases on doublets containing only left-handed fermions of different type.
- Discrete symmetries and their breaking in weak interactions.

  (To be continued in lecture 12.)
- Introduce electroweak symmetry breaking: Higgs mechanism.
  A subtle way of beating "symmetry enforces massless bosons"