Insights and puzzles in particle physics

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University of Bern

C. V. Raman Lecture
Indian Association for the Cultivation of Science
Kolkata, India, Dec. 10, 2013

Plan of talk

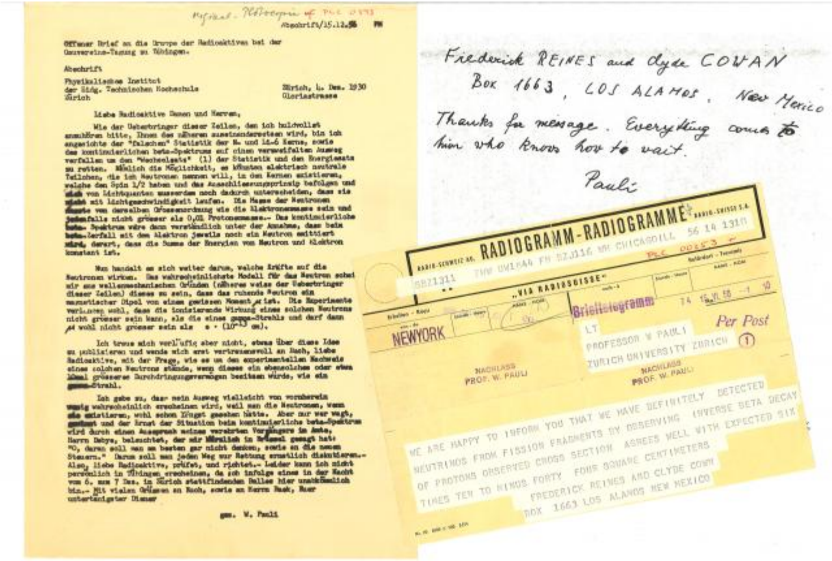
- During the last 100 years, a remarkable development took place in our understanding of particle physics.
- I plan to briefly review this development and discuss some qualitative features which gradually emerged.
- In particular, I intend to explain the prominent role played by gauge fields in our understanding of the laws of nature.
- On the way, I will draw your attention to some of the puzzles to which a solution is not in sight.

Atoms

- Bohr's model of the hydrogen atom $\Rightarrow$ quantum theory
- This development eventually led to a very thorough understanding of the structure of atoms, molecules, solids, ...
- Constituents of matter in that framework: nuclei + electrons
- Crucial properties of the constituents: mass, charge
  In atomic physics, the size and structure of the nuclei, magnetic moments etc. only matter at high precision

Neutrino

- The distribution of the decay products observed in β decay was puzzling. Is the energy not conserved ?
- The observed spectrum can be explained if a yet unknown particle is emitted together with the electron.
  Must be neutral and escape detection. Pauli 1930
- Experimental discovery Reines and Cowan 1956



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 Grössenordnung 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

Leptons

In today's terminology, Pauli predicted the electron neutrino, ν_e.
Both the electron and the ν_e have relatives, **leptons**.
Altogether 6 leptons, 3 families:

1897	e	ν_e	1956
1936	μ	ν_μ	1962
1975	τ	ν_τ	2000

Why 6 different "flavours" of leptons ?
Who ordered the muon ?

Rabi $\sim$ 1936

Neutron

- Discovery of the neutron Chadwick 1932

$\Rightarrow$ Nuclei $= \mathbf{p} + \mathbf{n}$

Simplified the picture considerably:

$\Rightarrow$ Matter built up from only 3 types of constituents: **e, p, n**

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- What binds the protons and neutrons together ?
Electromagnetic forces arise from photon exchange.
Photon is a massless particle ⇒ long range force
Exchange of massive particles ⇒ short range force

$$\mathbf{V}_{\text{em}} \propto \frac{\mathbf{1}}{\mathbf{r}} \qquad \mathbf{V}_{\text{strong}} \propto \frac{\mathbf{1}}{\mathbf{r}}\,\mathbf{e}^{-\frac{\mathbf{r}}{\mathbf{r}_0}} \qquad \mathbf{r}_0 = \frac{\hbar}{\mathbf{mc}}$$

long range — short range

Stueckelberg, Yukawa ∼ 1934

π-meson

- Range of nuclear force:

$$\mathbf{r}_0 = \frac{\hbar}{\mathbf{mc}} = O(10^{-15}\mathrm{m}) \qquad \Rightarrow \qquad \mathbf{mc^2} = O(200\ \mathrm{MeV}).$$

- Yukawa predicted a spinless particle which strongly interacts with **p** and **n** and has a mass around $\mathbf{mc^2} \simeq 100$ MeV.

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- Discovery of the π-meson: $\mathbf{m_\pi c^2} = 140$ MeV Powell 1947
- Around the same time, many other strongly interacting particles where discovered: **K**-mesons, hyperons, excited states of the nucleon, . . .

Refinement of the Yukawa potential

- Nonrelativistic potential models: Paris potential, Bonn potential, shell model of the nucleus

⇒ Nuclear structure, nuclear reactors, processes responsible for the energy production in the sun, α-decay, ...
were well understood already fifty years ago.

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- These phenomena concern interactions among nucleons with small relative velocities. Experimentally, it had become possible to explore relativistic collisions, but a description in terms of nonrelativistic potentials cannot cover these.

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- These phenomena concern interactions among nucleons with small relative velocities. Experimentally, it had become possible to explore relativistic collisions, but a description in terms of nonrelativistic potentials cannot cover these.
- Many attempts at formulating a theory of the strong interaction based on elementary fields for baryons and mesons were undertaken, Yukawa interaction for the strong forces, perturbation theory with coupling constants of order 1, ...

uncountable PhD theses 1945 -1965

Meson- und Hyperon Massendifferenzen

von **N. Straumann**
Institut für Theoretische Physik, Universität Zürich

(25. XI. 1961)

Summary. The mass differences of the various meson- and hyperon charge multiplets are calculated (π-, K-mesons, Σ, Ξ-hyperons). It is assumed that the theoretical masses of a charge multiplet are equal and that the experimental mass differences rest on self energy effects. The self energies are calculated on the basis of field theory to the order e^2 and $e^2 f^2$ (f = coupling constant of the strong interactions). The method is similar to the calculation of the nucleon mass difference by O'Raifeartaigh, Terreaux and Sredniawa[1]). We use the Prentki-d'Espagnat coupling. For π-mesons the purely electromagnetic self energy is dominant. For K-mesons this is smaller by a factor 3. The $e^2 f^2$-effect is about equal for both particles and has the opposite sign of the e^2-effect. Quantitatively, for a cut-off K_0 = nucleon mass, it is still too small by a factor 3–5 to overcompensate the purely electromagnetic self energy but it increases $\sim K_0^5$ (compared with $\sim K_0^2$ for the e^2-effect). The correct mass difference could be obtained for $K_0 \sim 1{,}6\, m_N$, which, however, is inconsistent with the quasistatic approximations used. – For the Σ's the π-interactions give no splitting of Σ^+ and Σ^- as a group theoretical argument shows. The K interactions yield a contribution much too small. For the Ξ's the π-interactions give the same result as for nucleons if one assumes global symmetry. The K-interactions contribute very little.

The connextion with other attempts based on dispersion relations and the experimental form factors of the nucleons is discussed.

Quantum field theory versus S-matrix theory

- Absolutely nothing worked even halfway, beyond general principles like Lorentz invariance, causality, unitarity

$\Rightarrow$ analyticity, dispersion relations, CPT theorem, spin + statistics

- There was considerable progress in renormalization theory, but faith in quantum field theory was in decline, even concerning QED (Landau-pole).
- Many people doubted that the strong interaction could at all be described by means of a local quantum field theory.
- Replace quantum field theory by S-matrix theory ?
  Heated debates Pietschmann, Eur. Phys. J. **H36** (2011) 75
- Regge poles Veneziano model 1968

Fifty years ago, the quantum field theory of the strong interaction consisted of a collection of beliefs, prejudices and assumptions. Only very few of these survived.

Quarks

- The pattern of the many strongly interacting particles observed by 1964 can qualitatively be understood with the quark model. Gell-Mann, Zweig 1964
- Three constituents of spin $\frac{1}{2}$ are needed: $\mathbf{u}, \mathbf{d}, \mathbf{s}$
- *Baryons* (protons, neutrons, hyperons . . .) contain 3 quarks

  $\mathbf{p} = \mathbf{uud} \qquad \mathbf{n} = \mathbf{udd} \qquad \mathbf{\Sigma}^+ = \mathbf{uus} \qquad \mathbf{\Xi^0} = \mathbf{uss}$
- *Mesons* consist of a quark and an antiquark:

  $\pi^+ = \mathbf{u}\bar{\mathbf{d}} \qquad \mathbf{K}^+ = \mathbf{u}\bar{\mathbf{s}} \qquad \rho^+ = \mathbf{u}\bar{\mathbf{d}}, \ldots$

$\Rightarrow$ Prediction: $\mathbf{\Omega}^- = \mathbf{sss}$ Gell-Mann 1962

- Experimental discovery: Brookhaven 1964

Heavy quarks

- Altogether 6 quark flavours are needed to account for all of the observed mesons and baryons. Also come in 3 families: pattern is similar to the one of the leptons.

	quarks				leptons		
1964	**u**	**d**	1964	1897	**e**	ν_e	1956
1974*	**c**	**s**	1964	1936	μ	ν_μ	1962
1995	**t**	**b**	1977	1975	τ	ν_τ	2000

1974* November revolution (discovery of the J/ψ)

Colour

- Quarks carry an internal quantum number
- Greenberg had introduced an internal degree of freedom of this type in 1964, referring to this as "parastatistics".
- In 1965, Bogolubov, Struminsky & Tavkhelidze, Han & Nambu and Miyamoto independently pointed out that some of the problems encountered in the quark model disappear if the **u**, **d** and **s** quarks occur in 3 states, "three-triplet model".
- Today, the new quantum number is called **colour**. Gell-Mann

first family	**u**	**u**	**u**	**d**	**d**	**d**	**e**	ν_e
second family	**c**	**c**	**c**	**s**	**s**	**s**	μ	ν_μ
third family	**t**	**t**	**t**	**b**	**b**	**b**	τ	ν_τ

Where are the quarks ?

- The quark model offers a remarkably simple and successful picture, explains the observed pattern of energy levels – but

  why do the quarks not show up in experiment ?

$\Rightarrow$ The existence of quarks was considered doubtful.
"Such particles [quarks] presumably are not real but we may use them in our field theory anyway . . ."

Gell-Mann, Physics **I** (1964) 63

- Quarks were treated like the veal used to prepare a pheasant in the royal french cuisine: the pheasant was baked between two slices of veal, which were then discarded (or left for the less royal members of the court).

$\Rightarrow$ Conceptual basis of such a cuisine ?

Standard Model

Our understanding of the laws of nature made remarkable progress in the 8 years between the discovery of the quark model (1964) and the discovery of Quantum Chromodynamics (1972).

Standard Model

All of the known forces except gravity are generated by **gauge fields**.

Gauge fields

- Prototype: electromagnetic field. Maxwell 1865

  Survived relativity and quantum theory, unharmed.

⇒ Quantum Electrodynamics, QED

- field picture: $\vec{\mathbf{E}}, \vec{\mathbf{B}}$ particle picture: γ photon

  Source of the field: electric charge.

- Key property: QED has a local symmetry, gauge invariance.

  Symmetry group: U(1)

  QED is the gauge field theory of U(1)

⇒ The symmetry completely fixes the e.m. interaction in terms of

$$\frac{\mathbf{e^2}}{\mathbf{4\pi}} = \frac{1}{137.035\,999\,074\,(44)}$$

Sommerfeld 1916

⇒ The e.m. interaction is understood, except for this mysterious number, which has resisted explanation for almost a century.

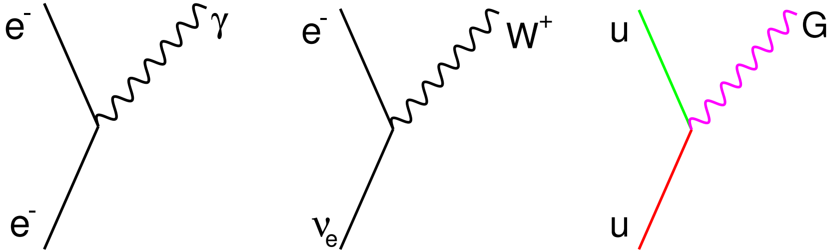
Generalization

- The symmetry group U(1) can be replaced by a larger group, for instance SU(2) or SU(3). Yang & Mills 1954
- Gauge invariance then requires the occurrence of more than one gauge field: 3 in the case of SU(2), 8 for SU(3).
- Standard Model: the interactions among the constituents of matter are generated by three distinct gauge fields.

interaction	group	dim.	particles	source	coupling
electromagnetic	U(1)	1	γ	charge	**e**
weak	SU(2)	3	$W^+ W^- Z$	flavour	$\mathbf{g}_\mathrm{w}$
strong	SU(3)	8	gluons	colour	$\mathbf{g}_\mathrm{s}$

- Alchemist sign for Standard Model: SU(3)× SU(2)× U(1)

Gauge field interactions



electromagnetic	weak	strong
QED	QFD	QCD
charge	flavour	colour
γ	$W^\pm$,Z	gluons
e	$\mathbf{g}_w$	$\mathbf{g}_s$

The Standard Model is a miracle

- Since a long time, we know that the microscopic world is governed by three types of interaction:

  electromagnetic, weak, strong

- These have qualitatively very different properties.
  - strong $\simeq$ weak ??
  - $\frac{1}{r}$ – potential describes an interaction of long range
    strong and weak interactions are of short range !
  - Photons can be seen by eye, gluons not,

    etc. etc. etc.

Why are the three interactions so different ?

The behaviour of the interactions at long distance differs

1. Photons do not have charge, but gluons have colour.

$\Rightarrow$
- Force between two electrons falls off with the distance.
- Force between two quarks does not fall off.

charge is free, but colour is confined.

2. In addition to the gauge fields, there is a **Higgs field**.

$\Rightarrow$ Suppresses the weak interaction at long distance.

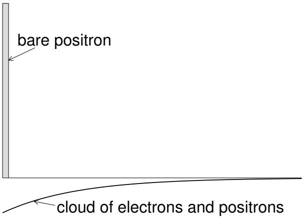
What makes the difference between QED and QCD ?

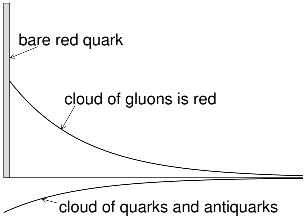
- Photons do not have charge.
- Gluons do have colour.

⇒ The e.m. and strong interactions
behave differently at long distance.

- Mathematical reason for the difference:
  - The gauge group of Quantum Electrodynamics is U(1)
    U(1) is abelian: $\mathbf{x}_1 \cdot \mathbf{x}_2 = \mathbf{x}_2 \cdot \mathbf{x}_1$
  - The gauge group of Quantum Chromodynamcs is SU(3)
    SU(3) is not abelian: $\mathbf{x}_1 \cdot \mathbf{x}_2 \neq \mathbf{x}_2 \cdot \mathbf{x}_1$

Compare structure of leptons and quarks





$$\mathbf{e} < \mathbf{e}|_{\text{bare}}$$

vacuum shields charge

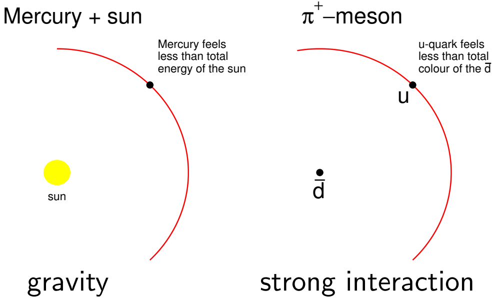
$$\mathbf{g}_s > \mathbf{g}_s|_{\text{bare}}$$

vacuum amplifies colour

$\Rightarrow$ The electromagnetic and strong interactions polarize the vacuum very differently.

Comparison with gravity

- source of gravitational field: energy
  gravitational field does carry energy
- source of gluon field: colour
  gluon field does carry colour



- Perihelion shift of Mercury: 43'' $=$ 50''– 7'' per century
  $\Uparrow$

Consequence of shielding/amplification

- Vacuum reduces electric field of a charged source.
  Vacuum amplifies gluonic field of a coloured source.
- The difference has dramatic consequences:
  although the Lagrangians of QED and QCD
  are very similar, the properties of the electromagnetic
  and strong interactions are totally different.
- Field energy surrounding a charged particle is finite.

$\Rightarrow$ charged particles can live alone.

- Field energy surrounding isolated quark $= \infty$
  only colourless states have finite energy.

$\Rightarrow$ colour is confined.

- $\nexists$ analytic proof that QCD does confine colour.
  Very good evidence from numerical simulations on a lattice.

Lattice approach to quantum field theory

- Quantum field theories can be approximated by the quantum mechanics of a finite number of degrees of freedom.
- The space-time continuum is replaced by a lattice of points.
- The remarkable progress achieved in the last couple of years allows to accurately calculate the masses of the lightest mesons and baryons from lattice versions of QCD.

$\Rightarrow$ Provides a very thorough check of the claim that the quarks are bound together with a nonabelian gauge field.

Force between colourless objects

- nuclear forces = van der Waals forces of QCD.
- At long distance and disregarding the e.m. interaction, the force between two nucleons is dominated by the exchange of the lightest strongly interacting particle: the π-meson.

⇒ Yukawa formula valid at long distance: $\mathbf{r_0 = \dfrac{\hbar}{m_\pi c}}$ $\surd$

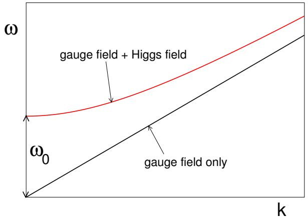
Higgs mechanism

1964

Higgs	independently
Brout & Englert	discovered the
Hagen, Guralnik & Kibble	Higgs mechanism

- scalar field ↔ particle without spin
  Higgs field ↔ Higgs particle
- Higgs field may pick up a vacuum expectation value.
  Particle picture: vacuum = condensate of Higgs particles.
- Particles that interact with the Higgs particles (in particular also gauge particles) feel the presence of this medium.

Penetration depth, range of interaction



$$\hbar\omega_0 = mc^2$$

$\Rightarrow$ gauge particles pick up mass

- Waves with $\omega < \omega_0$ cannot propagate.
- Penetration depth for low frequencies: $r_0 = \dfrac{c}{\omega_0} = \dfrac{\hbar}{mc}$
  - Exchange of massless particles: $V \propto \dfrac{1}{r}$
  - Exchange of massive particles: $V \propto \dfrac{e^{-\frac{r}{r_0}}}{r}$

Simplest example

- Suppose there is a charged Higgs field
- Suppose that this field picks up a vacuum expectation value
- Electromagnetic waves interact with the condensate

$\Rightarrow$ Photons pick up mass

$\Rightarrow$ Electromagnetic interaction ceases to be of long range

$\Rightarrow$ Disagrees with observation

$\Rightarrow$ A charged Higgs field does not exist

Gauge field theory of the weak interaction

- The properties of the weak interaction can be understood if
  (1) there is an SU(2) gauge field;
  (2) there is an SU(2) doublet of Higgs fields (4 real fields).
  Glashow, Salam, Weinberg 1967

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- Experimental discovery ATLAS & CMS at CERN LHC 2012

Consequence for strength of weak interaction

- Strength of the interaction is reduced:

$$\frac{g_W^2}{4\pi r} \Rightarrow \frac{g_W^2}{4\pi r} \cdot e^{-\frac{r}{r_0}} \qquad r_0 = \frac{\hbar}{m_W c}$$

- The W-particles interact vigorously with the Higgs condensate.

$\Rightarrow$ m_W is large: $m_W = 85.673 \pm 0.016\ m_{proton}$ $\qquad m_W > m_{Fe}$

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⇒ $\mathbf{m}_W$ is large: $\mathbf{m}_W = 85.673 \pm 0.016\ \mathbf{m}_{\text{proton}}$ $\qquad \mathbf{m}_W > \mathbf{m}_{Fe}$

⇒ Penetration depth of the weak interaction is small:

$$\mathbf{r}_0 = \frac{\hbar}{\mathbf{m}_W \mathbf{c}} \simeq 2.5 \cdot 10^{-18}\ \text{m}$$

⇒ Weak interaction is of very short range.

- Effective strength at low energies:

$$\int \mathbf{d}^3\mathbf{r}\, \frac{\mathbf{g}_W^2}{4\pi\mathbf{r}} \cdot \mathbf{e}^{-\frac{\mathbf{r}}{\mathbf{r}_0}} = \mathbf{g}_W^2 \mathbf{r}_0^2$$

⇒ At low energies, the weak interaction is weak.

Transparency of the vacuum

vacuum = condensate of Higgs particles.

- The Higgs particles do not carry charge.

$\Rightarrow$ Photons do not notice these.

$\Rightarrow$ Vacuum is transparent for photons.

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- The Higgs particles do carry flavour.

⇒ W,Z do take notice.

⇒ W,Z-waves of low frequency cannot propagate.

⇒ For such waves, the vacuum is opaque.

Masses of the leptons and quarks

- The leptons and quarks also interact with the condensate.

$\Rightarrow$ pick up mass.
Size of the lepton and quark masses is determined by the strength of their interaction with the Higgs fields.

- Unlike for the gauge particles, the symmetries of the Standard Model do not determine the strength of this interaction.
- Pattern of lepton and quark masses is bizarre:
$\mathbf{mc^2}$ ranges from $\sim 10^{-2}$ eV to $\sim 10^{11}$ eV.

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- Pattern of lepton and quark masses is bizarre:
  $\mathbf{mc^2}$ ranges from $\sim 10^{-2}$ eV to $\sim 10^{11}$ eV.
- The electron happens to pick up only little mass.

$$\mathbf{a}_{\text{Bohr}} = \frac{\mathbf{4\pi}}{\mathbf{e^2}} \cdot \frac{\hbar}{\mathbf{m_e c}}$$

⇒ Bohr radius is much larger than the radius of the proton.

Precision tests of Standard Model: magnetic moments

- Dirac equation predicts: $\mu = \frac{e}{m}$
- Electron magnetic moment known to phantastic precision:

  $$\mu_e = \frac{e}{m_e} \times 1.001\;159\;652\;180\;76(27)$$

  Experimental uncertainty only shows up in the 13$^{\text{th}}$ decimal.

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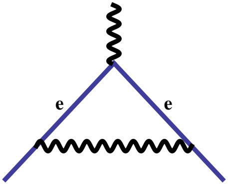
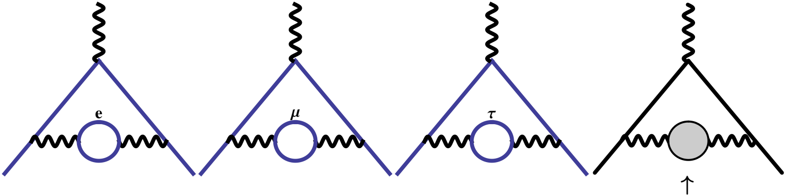
- Leading correction in QED: Schwinger 1948

$$\mu = \frac{e}{m}\left\{1 + \frac{e^2}{8\pi^2} + O(e^4)\right\}$$

$$\frac{e^2}{8\pi^2} = 0.00116\ldots$$



Contribution from higher orders



- Accuracy of prediction is limited by uncertainty in **e**.
- Contributions from QCD are too small to test our understanding of the strong interaction with $\mu_{\mathbf{e}}$.
- Same applies to contributions from QFD.
- $\mu_{\mathbf{e}}$ does offer a test of QED at breathtaking precision: a difference can be seen only in the 12^{th} decimal
  Experiment − Theory $= -1.09 \pm 0.83 \cdot 10^{-12}$

Magnetic moment of the muon

- Experiment: $\mu_\mu = \frac{\mathbf{e}}{\mathbf{m}_\mu} \times 1.001\,165\,920\,89(63)$

  experimental uncertainty shows up in the 10^{th} decimal

- Theory: $\mu_\mu = \frac{\mathbf{e}}{\mathbf{m}_\mu} \times 1.001\,165\,917\,95(62)$

  Nyffeler 2013

- Contributions from QCD and QFD do matter here:
  - QCD: hadronic vac. pol. $\sim$100$\times$exp. error
  - QCD: light-by-light scattering $\sim$ 2$\times$exp. error
  - QFD: $\sim$ 2$\times$exp. error
- Experiment – Theory amounts to 4.7$\times$exp. error

$\Rightarrow$ Standard model prediction for μ_μ is off by 3.3 σ.

Puzzling results for muonic hydrogen

- Hydrogen atoms formed with $\mathbf{p} + \mathbf{e}$ or with $\mathbf{p} + \mu$.
  Lamb shift can be measured very accurately.
- Main uncertainty in the SM prediction for Lamb shift stems from the radius of the charge distribution in the proton: $\mathbf{r_p}$.
  Can use the measurement of the Lamb shift to determine $\mathbf{r_p}$.
  Independently, $\mathbf{r_p}$ can be measured in $\mathbf{e} + \mathbf{p} \rightarrow \mathbf{e} + \mathbf{p}$.
- Juicy discrepancy in results for proton charge radius:

  $\mathbf{p} + \mathbf{e}$ $\quad \mathbf{r_p} = 0.8775(51) \cdot 10^{-15}$ m $\quad$ CODATA 2010

  $\mathbf{p} + \mu$ $\quad \mathbf{r_p} = 0.84087(39) \cdot 10^{-15}$ m $\quad$ PSI 2013

  Totally unexpected, no plausible explanation so far.
  The quoted numbers amount to a discrepancy of 7 σ !

Implication ?

Three possibilities, for μ_μ as well as for $\mathbf{r_p}$:

- Physics beyond the Standard Model ?
  Lepton universality: $\{\mathbf{e}, \nu_\mathbf{e}\}$, $\{\mu, \nu_\mu\}$, $\{\tau, \nu_\tau\}$
  only differ in the interaction with the Higgs particles.
- Error in the evaluation of the SM prediction ?
- Did something go wrong with the experiment ?

Hints at deviations from the Standard Model are very rare.
Need to treat them with care – prejudice does not help.

Summary

IG Physik, Gesellschaft mit besonderer Haftung, advertisement ca. 1973

Im Falle eines Falles
klebt ein EICHFELD
wirklich alles !

Bezugsquellennachweis

J. C. Maxwell, Royal Society Transactions 155 (1865) 459

H. Weyl, Z. Phys. 56 (1929) 330

C. N .Yang and R. Mills, Phys. Rev. 96 (1954) 191

Short distance

- At short distance (1 TeV $\leftrightarrow$ $2{\cdot}10^{-19}$ m) all of the forces obey the inverse square law.

$$\mathbf{V} = \text{constant} \times \frac{\hbar \mathbf{c}}{\mathbf{r}} \qquad \text{interaction energy}$$

- The constant is a pure number.

$\Rightarrow$ Interaction strength is fixed by 3 pure numbers.

e.m.	weak	strong
$\frac{\mathbf{e}^2}{4\pi}$	$\frac{\mathbf{g}_w^2}{4\pi}$	$\frac{\mathbf{g}_s^2}{4\pi}$

Long distance

- Vacuum amplifies the interaction between quarks

$\Rightarrow$ Colour is confined

- Vacuum is opaque for the gauge fields of SU(2).

$\Rightarrow$ At low energies, the weak interaction freezes in.

- Heavy quarks and leptons decay into the light ones.
  In stable matter only **e, u, d**.
- At low energies, Standard Model reduces to QED + QCD: precision theory for the structure of matter.
  Weak interaction only generates tiny, calculable corrections.

Beyond the Standard Model

- Gravity $\cap$ Quantum theory $= \emptyset$
  Standard Model is only an effective theory for 'low' energies.
  Quite a few layers of structure seen at the present resolution.
  No further layers all the way to ℓ_{Planck} ?

$$\ell_{\text{Planck}} = \sqrt{\frac{G\,\hbar}{c^3}} = 1.6 \cdot 10^{-35}\ \text{m}$$

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- Anything that carries energy generates gravity.
  Why does gravity not take notice of the Higgs condensate ?

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- Astronomical observations: $\exists$ Dark Energy ? $\exists$ Dark Matter ?
- Anything that carries energy generates gravity.
  Why does gravity not take notice of the Higgs condensate ?
- Why do baryons dominate the visible matter in our vicinity ?
  Difficult to understand if the proton does not decay – does it ?
  CP violation is necessary for baryogenesis, too.
  Is observed and accounted for in SM, but not understood.

Beyond the Standard Model

- Supersymmetric extensions of the Standard Model do contain candidates for Dark Matter, but where are the super-partners ?
- Why are there so many lepton and quark flavours ?
- Origin of the bizarre mass pattern of the leptons and quarks ?

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Does explain the occurrence of mesons and baryons and describes their properties, albeit only approximately.

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Compared to this, the Standard Model leaves much to be desired.