Notes on SM History

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May 5, 2022

Chapter 1

A mnemonic history

One could argue that the beginning of the SM history coincides with the beginnings of modern particle physics. Since that depends on unifying relativity, quantum mechanics, and field theory, one could arguably even take Maxwell's equations as a starting point. There were also many interesting ideas that were not pursued or turned out not to be correct yet still played some role in the history; I will not discuss these. In some cases I may miss some discoveries that were also important but less celebrated.

Given these ambiguities and the fact that I am not at all a real historian, one might call what follows an "approximate" history. As I was writing this, I realized that I was trying to tell a story, i.e. to write it in a way that one development would make sense or feel motivated given a previous development. Usually that is a bit of an oversimplification, but it helps me remember why certain discoveries were significant, where some nomenclature comes from, and what it means. Hopefully it also helps reveal how physicists think, how we are led to discoveries, and ultimately why we believe our theories. So with these advantages in mind, I rather decided to call it a "mnemonic" history.

Also while I was writing this, I learned a bunch of facts that I found interesting but are probably a bit off-topic. Hence this mnemonic history is densely packed with footnotes. For example I decided to start listing Nobel prizes for some reason. By the time I realized doing this is tedious and doesn't teach much, I somehow already felt pot-committed, so I ended up seeing this habit through to the bitter end.

1.1 The fundamentals

In 1897 J.J. Thomson did experiments with cathode rays[1] from which he concluded that electric charge must be carried by particles with high charge-to-mass ratio, the electrons[2] To explain why atoms are overall electrically neutral, Thomson guessed that electrons are distributed in a sea of positive charge, which is the well known *plum pudding model*. This was disproved by Rutherford in his famous gold foil experiment [1], in which he discovered the atomic nucleus. Shortly thereafter, he discovered the proton [2]. Bohr proposed his model [3] of hydrogen, supposing it to be made of a proton and an electron, which agreed well with experiment[3]. Extending this theory to heavier elements by supposing they are also made of only protons and neutrons however fails, since e.g. helium is four times as heavy as hydrogen. This difficulty would not be sorted out until the early 1930s, when Chadwick discovered [4] the neutron[4].

These early discoveries successfully explained many details of the atom; however the fact that atomic nuclei are made of particles with only positive or zero electric charge still required explanation. Hence for some time, physicists knew there must be some *strong force* that opposes Coulomb repulsion and binds nucleons into nuclei. Such particles held together by strong interactions are called *hadrons*. Nowadays we also use the terms *meson* and *baryon* to refer to hadrons made of two quarks and three quarks, respectively[5].

Around this time, physicists were also beginning to see the particle nature of light. In particular, Planck proposed [5] that light may come in discrete packets of energy in order to avoid the ultraviolet catastrophe[6]. Einstein took this proposal seriously [6], and used it to explain the photoelectric effect[7]. A careful study [7] of the photoelectric effect by Millikan showed

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[1] In a small vacuum chamber with two electrodes, if a voltage is applied between them, electrons will move between them. Televisions used to work by cathode ray tubes, where these electrons are deflected by magnetic fields to make images on the screen.

[2] He received the 1906 Nobel in physics for this work.

[3] He got the 1922 Nobel for his contributions understanding atomic structure.

[4] 1935 Nobel for him.

[5] This naming scheme comes from particle weights. At the time, known leptons were light, baryons were heavy, and mesons were somewhere in the middle. In retrospect it would have been nicer to name them something like n-hadrons, but alas it would take several decades for us to see that hadrons are made of quarks.

[6] 1918 Nobel.

[7] 1922 Nobel for him.

that Einstein's interpretation explained the photoelectric effect well[8]. Finally Compton showed[9] that light scattered from a particle shifts by the Compton wavelength

$$\lambda_c = \frac{\hbar}{2mc}, \tag{1.1}$$

where m is the target particle's mass, which one can derive by assuming light is made of particles with zero rest mass [8]. Altogether these discoveries convinced physicists light behaves as a particle at short enough length scales, which is the usual photon.

If light is to be quantized, it requires a theory that knows about both quantum mechanics and special relativity, i.e. it needs QFT. The standard line of thinking can be cast in this way: One starts with the Schrödinger equation [9; 10; 11; 12] for a spinless, non-relativistic particle of mass m in the position basis,

$$i\hbar\partial_t\psi = -\frac{\hbar^2}{2m}\nabla^2\psi. \tag{1.2}$$

If we instead use a relativistic Hamiltonian and square the differential operators on each side, we get the *Klein-Gordon equation* [13; 14]

$$-\hbar^2\partial_t^2\psi = \left(-\hbar^2c^2\nabla^2 + m^2c^4\right)\psi. \tag{1.3}$$

While this is at least relativistically sensible, one can show that this squaring of operators leads to state normalization being time-dependent, i.e. probability is not conserved. The situation was finally rescued by Dirac[10], who realized that one could have a relativistically sensible equation that is first-order in its operators by introducing some matrices and a spin component to the wavefunction [15; 16]. The result is the *Dirac equation*

$$i\hbar\partial\!\!\!/\psi = mc\psi. \tag{1.4}$$

The corresponding Hamiltonian for the Dirac equation is traceless, which tells you that the energy eigenvalues cancel out, i.e. it suggests there are states of negative energy. These negative energy states indicate that the theory has no ground state. In order to prevent this infinite cascade into increasingly negative energies, he speculated that these infinitely many states

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[8] He got the 1923 Nobel in part for this reason.

[9] He shared the 1927 Nobel for this.

[10] Dirac and Schrödinger shared the 1933 Nobel.

are already occupied, which is referred to as the *Dirac sea*; the Pauli exclusion principle then prevents this infinite descent. If an electron in the sea were excited, it would leave behind a vacancy that would manifest itself as a positively charged particle. This was the prediction of the existence of the positron, which was discovered[11] in 1932 by Anderson [17]. Later Stückelberg [18] and Feynman [19] would introduce the modern interpretation of the positron: rather than being a hole left in the Dirac sea, the previously negative energy states are to be understood as the positive energy states of a different particle.

One of the last kinds of fermions needed to complete our particle collection are the neutrinos. Before 1930, there was a problem with β-decay which is any decay emitting an e^+ or e^- from an atomic nucleus: Energy was not conserved. In particular if one assumes a general β-decay process functions like

$$A \to B + e^-, \tag{1.5}$$

one can use conservation of four-momentum to find the electron energy. The measured energy was found to fluctuate and be smaller than what four-momentum conservation delivers. Pauli suggested[12] that this missing energy lies with an as-yet-undetected, weakly interacting particle, the electron neutrino. The electron neutrino would not be discovered[13] until the mid 1950s by Cowan and Reines [20].

1.2 Weak and strong forces

In the early 1930s, Fermi published[14] his theory of the β-decay [21]

$$n \to \mathrm{p} + e^- + \bar{\nu}_e. \tag{1.6}$$

He introduced an effective 4-point interaction directly linking the four particles in the above process. Shortly thereafter, Yukawa [22] put forward that

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[11] 1936 Nobel.

[12] Rather than being documented in a publication, this seems to come from a letter written by Pauli addressed to a conference in Tübingen. It opens, “Liebe Radioaktive Damen und Herren”.

[13] 1995 Nobel.

[14] Apparently he originally attempted to publish it in *Nature*, but they rejected it because it because “it contained speculations too remote from reality to be of interest to the reader”.

this interaction should include another field with corresponding quantum that mediates this interaction[15], sort of like how the photon mediates the electromagnetic interaction. Another salient point of this paper is the introduction of the *Yukawa potential* giving the potential of a gauge boson of mass m:

$$V(r) = -g^2 \frac{e^{-\alpha m r}}{r}. \tag{1.7}$$

Here g is the gauge coupling and r is the interaction range. One sees that massless gauge bosons have a Coulomb-like potential, while massive ones are suppressed exponentially[16], which gives an explanation why the weak force has a short interaction range. Besides already hinting massive weak bosons, this paper is considered to be one of the first theories of the strong force; from this perspective the proton and neutron exchange massive mesons, which therefore have a limited interaction range[17].

An early experimental search of cosmic ray[18] measurements using cloud chambers (see Fig. 1.1) found the muon [24], which was originally mistaken[19] as the meson that Yukawa suggested. An experiment in the late 1940s showed that the muon does not interact very strongly with atomic nuclei [25], which rules it out as the strong force mediator. Thankfully for Yukawa the pion was discovered [26] in 1947[20].

In the late 1940s and early 1950s, the *kaon* (K) [27] and *lambda* (Λ) [28] hadrons were discovered. A kaon consists of light quark and a strange, while a lambda baryon binds two light quarks with one from a higher generation.

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[15] Nowadays we designate as *Yukawa interaction* any interaction between Dirac fields and scalar fields of the form $g\bar{\psi}\phi\psi$ or $g\bar{\psi}i\gamma_5\phi\psi$.

[16] One can also show that the Fourier transform of this potential is the propagator, which we will discuss later.

[17] 1949 Nobel.

[18] A *cosmic ray* is a high energy proton or atomic nucleus that originates somewhere from space. They were discovered in the early 1910s by Hess, which got him the 1936 Nobel.

[19] Indeed the muon and pion masses are pretty close to each other, sitting at about 106 MeV and 140 MeV, respectively.

[20] And got Powell the 1950 Nobel for it. It is actually a bit puzzling that he is the only recipient of this prize, most obviously because only three other scientists were on his team. Furthermore this prize credits him for his “development of photographic method for studying nuclear processes”, even though this method was pioneered by other physicists such as Blau and Wambacher.

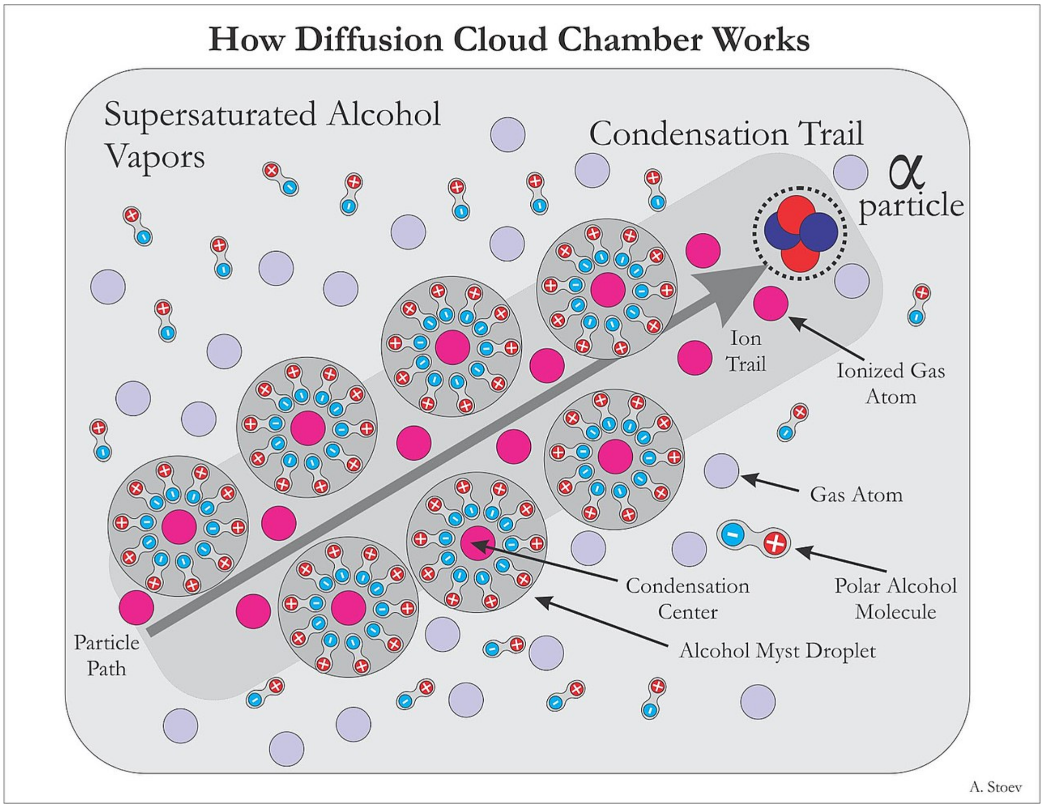

Figure 1.1: Cloud chambers consist of a sealed environment with some vapor of e.g. alcohol. As a charged particle moves through the vapor, it knocks electrons off the gas; the resulting ions attract the polar molecules, which leaves a visible trail for a short time. To identify particles, you can see e.g. if they were deflected. C. T. R. Wilson is generally credited as the inventor of cloud chambers, and he shared the 1927 Nobel in physics for it. They were extremely popular to use in experiment for finding particles until the later invention of the bubble chamber. Image taken from Wikipedia [23].

Strangeness[21] was originally proposed as a conserved quantity to explain the relatively long lifetimes of these particles [29; 30; 31; 32]. Ne'eman [33], Gell-Mann [34], and Zweig [35] proposed[22] that these hadrons could be classified according to the irreducible representations of SU(3), a viewpoint which Gell-Mann called the *eightfold way*[23], examples of which are illustrated graphically in Fig. 1.2. Gell-Mann referred to the fundamental units as *quarks*[24]. At first it was not clear that this quark viewpoint was more than a purely mathematical construction, however deep inelastic scattering experiments at the Stanford Linear Accelerator (SLAC) showed that protons are made of smaller particles, and are therefore not elementary [36; 37]. This alone did not convince the community that quarks were real[25], but subsequent discoveries would solidify the quark model.

From here it was shown possible to formulate a QFT for the strong interaction based on SU(3) [39], which we call quantum chromodynamics (QCD). The mediators are called *gluons* with the adjoint representation delivering eight possible color combinations. Gross, Wilczek [40] and Politzer [41] demonstrated *asymptotic freedom*[26] in this QFT, i.e. they showed that the strong coupling decreases with increasing interaction strength, which is consistent with the fact that one does not observe free quarks[27]. This theoretical observation is buttressed by strong coupling expansions in the lattice formulation, introduced by Wilson [42], which show that the potential energy between two infinitely heavy quarks grows linearly with increasing separation.

We round out this section with a short timeline of discoveries of the remaining QCD particles. In 1974 the discovery of the J/Ψ-meson or *psion*[28] at both Brookhaven National Lab (BNL) and SLAC [43; 44] demonstrated

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[21] We now identify strangeness S as

$$S \equiv \#\,\text{anti-strange quarks} - \#\,\text{strange quarks}.$$

[22] Gell-Mann would receive the 1969 Nobel for his contributions to understanding elementary particle classification.

[23] This name is inspired by the eightfold path of Buddhism.

[24] Gell-Mann borrows this name from an excerpt of James Joyce's *Finnegan's Wake* that begins "Three quarks for Muster Mark". Gell-Mann was a bit of a fanciful guy I guess.

[25] For a while it was fashionable to refer to rather refer to nucleon constituents as *partons*, a term coined by Feynman.

[26] They got the 2004 Nobel for this.

[27] At least not at typical temperatures and densities.

[28] The J/Ψ consists of a $\bar{c}c$ pair. This is also sometimes called *charmonium*.

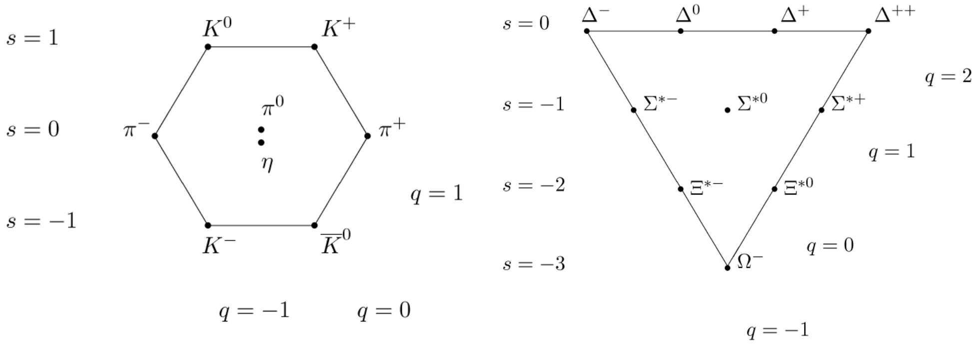

Figure 1.2: *Left*: Spin-0 pseudo-scalar meson octet. *Right*: Spin-3/2 baryon decuplet. The s represents strangeness, with all particles in the same horizontal row having the same strangeness. Electric charge is represented by q, with all particles along the diagonal having the same electric charge. Images taken from Wikipedia [38].

the existence of the charm quark[29], adding further evidence to the validity of the quark model. The J/Ψ discovery marks the beginning of a period of rapid discoveries in particle physics sometimes referred to as the "November Revolution". The existence of the bottom quark was demonstrated in 1977 at Fermilab [45] when the Y-meson[30] was discovered. In 1979 we found experimental evidence for the gluon via indirect observations [46] at the Deutsches Elektronen-Synchrotron (DESY). In part because it is the heaviest quark, the top quark would not be discovered until 1995 [47; 48] at Fermilab.

1.3 Unification

In the mid 1950s, Lee and Yang [49] suggested possible experimental tests to search for parity violation in weak interaction processes[31]. Shortly thereafter, Wu et al. [50] demonstrated parity violation in the β-decay of ^{60}Co, a result which was verified by Garwin et al. [51]. The theory of the weak interaction was extended by Gell-Mann and Feynman [52] to accommodate parity violation by introducing vector-axial currents. That β-decay proceeds through

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[29] Richter and Ting got the 1974 Nobel prize in physics for this.

[30] A Y-meson is a $\bar{b}b$ bound state. This is sometimes called *bottomonium*.

[31] Lee and Yang won the 1957 Nobel prize for this.

vector-axial currents was experimentally verified shortly thereafter [53].

The unification of the weak and electromagnetic forces began already with Glashow in 1961 [54], where he puts forward the SU(2) × U(1) symmetry group. Still, this theory was not known to be renormalizable. Also the weak interaction is short range, but this suggests that the mediating boson should be massive according to Yukawa. On the other hand, massive gauge bosons superficially spoil gauge invariance.

In superconductivity, Ginzburg-Landau theory [55] gives solutions with effective mass. Nambu applied[32] this to particle physics [56; 57; 58], but this implied the existence of Goldstone modes that are not observed. Higgs [59] and Brout and Englert [60] noticed[33] that by strategically choosing the gauge, one can simultaneously eliminate the Goldstone modes, add a mass term to gauge bosons, and a scalar boson, the Higgs boson.

The original Higgs-Brout-Englert mechanism was demonstrated only for massive QED; Kibble extended this idea to non-abelian groups [61]. Weinberg [62] and Salam [63] applied Kibble's results to Glashow's SU(2) × U(1) idea[34]. They demonstrated that one can generate masses for weak gauge bosons along with electrons and muons, while still leaving neutrinos massless. This approach also predicted neutral weak currents, which were discovered shortly thereafter by the Gargamelle experiment [64]. The W and Z bosons would be discovered at the European Organization for Nuclear Research (CERN) in the early 1980s [65; 66].

In 1963, Cabibbo introduced the *Cabibbo angle* allowing for quark mixing in weak interactions [67] to explain the lifetimes of heavier hadrons. The suppression of flavor changing neutral currents was explained in the early 1970s through the GIM mechanism [68], but in order for this mechanism to work, one needed full doublets of quarks and leptons. Then Kobayashi and Maskawa predicted the existence of a third generation [69], since three quark generations are the minimal amount needed to allow CP violation in the quark sector[35]. The full quark mixing matrix is known as the CKM matrix. Neutrino mixing is also handled through a mixing matrix, the so-called PMNS matrix.

In the early 1970s, t'Hooft and Veltman showed[36] these theories are renor-

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[32] 2008 Nobel prize.

[33] Higgs and Englert received the 2013 Nobel for this.

[34] And shared the 1979 Nobel for it.

[35] They shared the 2008 Nobel along with Nambu.

[36] 1999 Nobel prize for them.

malizable [70]. Together the Higgs mechanism and renormalizability of the SM allow one to consistently generate gauge boson masses while ensuring its applicability at all energy scales. Furthermore CERN's 2012 discovery of the Higgs boson [71; 72] shows that Higgs mechanism corresponds to reality, rather than being just a mathematical trick to consistently approach massive elementary particles.

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