

History of Particle Physics (lecture notes)

Particle physics proper is almost entirely an $\geq 20^{\text{th}}$ century development, though of course it builds on prior knowledge.

Its roots and program, i.e. "Analysis and Synthesis" or "Reductionism", are related to the tradition of Atomism, which goes back at least to the ancient Greeks. The basic idea is that a fruitful strategy for understanding how the physical world works is to study its very smallest components, understand those thoroughly, and then build back up. That program has worked remarkably well.

Why? Because (it turns out) there are only a manageable number of building blocks, they have reproducible, "reasonably simple" properties, and they interact locally.

On the other hand it is appropriate to mention that the etymology of "A-Tom" is "not-divisible", whereas the possibility of manifold transmutations is a major feature of modern particle physics.

Also, traditionally atoms were viewed as "hard, massy, and impenetrable" (Newton): Implicitly, it was assumed

that just one atom, at most, would occupy a given place at a given time. Reality, as we'll see, is much more flexible. For this reason, the name "particle physics" can be misleading. Indeed fields, not particles, are the primary ingredients of our modern Standard Model.

The two thick volumes "The World of the Atom", 2 volumes, ed. H. Boorse and L. Motz (Basic Books, 1966) collect important extracts from primary sources, with commentary. I've found them to be a wonderful source of perspective, insight, and inspiration. Weinberg's "The Discovery of Subatomic Particles", <http://amzn.to/18dugIO> is much slimmer and more narrowly focused, but also highly recommended.

Particle physics in a recognizably modern sense begins with the discovery of the electron, by J. J. Thompson in 1897. What he discovered, more precisely, is that one component of gaseous discharges in Crookes tubes - the cathode rays - responded to electric and magnetic fields, in a way consistent with its being a stream of particles with fixed charge-to-mass ratio. That ratio corresponds, of course, to our e/m_e . This simple result held, whatever the substance being decomposed. (By contrast, the "anode rays" are much more complicated and non-universal.)

The next elementary particle discovery was, by contrast, almost entirely theoretical. This was the discovery of the photon. Photons had, of course, been observed since long before humans walked the Earth. But they were not clearly recognized as particles prior to revolutionary developments inaugurated by Einstein's photoelectric theory, starting in 1905. Indeed the wave theory of light and then its fusion into electromagnetic theory was a major triumph of nineteenth century physics, both theoretical and experimental. How both conceptions can be valid, though they are in some respects contradictory, is the heart of quantum mechanics, and in particular of Bohr's "complementarity". The modern concepts of quantum field theory transcend this duality. Neither "particle" nor "wave" does justice to the precise formulation that emerges from our equations.

A rapid-fire sequence of developments in the years 1911-1913 gave us, in essence, the *picture* of atoms we still use today. (The *equations*, i.e. modern quantum theory, took another 15 years or so to mature.) These were the Geiger-Marsden experiment, its interpretation by Rutherford, and finally Bohr's atomic model.

The Geiger-Marsden experiment is in many ways the template for experimental particle physics, and specifically scattering experiments. One probes the deep interior of matter by bombarding with energetic projectiles and studying their deflection; one must then reconstruct the responsible forces.

[technical discussion of Rutherford scattering here in lecture, following:
en.wikipedia.org/wiki/Rutherford_scattering]

(For more on these topics, start with the appropriate wikipedia articles: Geiger-Marsden experiment, Bohr model.)

Rutherford-Bohr "Solar system" model of atoms: Mass and positive charge concentrated in a tiny nucleus, a surrounded by a cloud of electrons. The cloud is bound by electric forces, and is governed by the rules of quantum theory.

By comparison, the nature of atomic nuclei was quite mysterious. Radioactivity revealed a bewildering variety of strange transformations, which were given names - α , β , γ radiation. Some regularities were codified, but there were no analogues of Newton's, Maxwell's, or Einstein's equations in play.

A major advance was Chadwick's discovery of the neutron, in 1932. It is the prototype of a "missing mass" experiment. More here: hyperphysics.phy-astr.gsu.edu/hbase/particles/neutrndis.html.

With that discovery the crude but still very useful and essentially correct picture of atomic nuclei, according to which they are built up from protons and neutrons, was in place. (Its rigorous content is a classification of nuclei by baryon number and electric charge. Traditional "nuclear physics" uses semi-empirical potentials and quantum many body theory to go much further in detailed model building. In principle QCD should provide a microscopic foundation for nuclear physics, but it has proved challenging to fulfill that promise. I'll say more about this later, when we discuss the quark model.)

Another spectacular advance, also in 1932, was the discovery of the antielectron, or positron, by Anderson. More here: en.wikipedia.org/wiki/Positron. That discovery confirmed theoretical ideas coming out of the Dirac equation and early quantum field theory. (I'll say more about this later, when we discuss charge conjugation symmetry.)

For many years cosmic rays provided the highest energy "particle beams". Their study, particularly using photographic emulsions, led to several important discoveries: π^\pm and μ particles, K particles. The π^\pm were not entirely unexpected, thanks to Yukawa's theory of the (tail of the) strong force. μ and K provided the first glimpses of the "family problems" that led to many entertaining adventures and still vex us today.

Quantum electrodynamics (QED) developed in parallel to this work. It had rather a different character. The crucial experiments (Lamb shift, electron magnetic moment) were low-energy precision, as opposed to high-energy exploratory, efforts. The relevant theory, involving mathematics of profound daring and intricacy, gave new life to quantum field theory in general. The renormalization concept, which was essential to interpreting the calculations, had a profound influence on later developments.

Systematic follow-up of these discoveries required specialized accelerators, which are substantial engineering projects. A series of such machines, operating at ever-higher energies, have dominated the

experimental side of particle physics since the early 1950s.

Major discoveries from the early years of accelerator physics include the existence of a very large number of unstable strongly interacting particles ("resonances") and the regularities of weak decays. We will discuss these discoveries more systematically over the next few "Survey" lectures.

[This historical sketch gets even sketchier below, as I mention topics we'll be discussing at length later in the course.]

Eventually these discoveries were incorporated into impressive semi-phenomenological theories: the quark model of hadrons, and the V-A theory of weak interactions, which of course we'll also survey.

Symmetry and its breaking emerged as dominant themes, permeating these theories.

The discovery of parity violation, CP violation, and neutrinos in several varieties were major highlights from this era.

Deep inelastic scattering experiments, using electrons and positrons (and later neutrinos) to probe the interior of protons and neutrons, gave shockingly simple results - 'scaling' - that could be interpreted using quantum field theory concepts in a seemingly slightly inconsistent way (parton model).

In a brief interval of time around 1970 a remarkable synthesis of ideas took place, resulting in the modern Standard Model. It will be our main concern in this course. The Standard Model remains as the firm foundation for fundamental physics today, unshaken by scrutiny at far higher energies and with far greater precision than the clues from which it was derived.

The Standard Model has two parts. Quantum chromodynamics (QCD) is the theory of the strong force, which binds quarks and gluons into hadrons, including protons and neutrons. QCD arose out of a rigorous analysis of deep inelastic scattering in quantum field theory, through the concept of asymptotic freedom. It is a gauge theory, based on the symmetry group $SU(3)$ ("color symmetry").

Electroweak theory, also sometimes called the Weinberg-Salam model, is also a gauge theory, based on the symmetry group $SU(2) \times U(1)$. As the name

suggests, it includes QED as its low-energy limit. The $SU(2)\times U(1)$ electroweak theory emerged from the rigorous application of quantum field theory, supplemented by ideas from superconductivity (!), to the V-A theory.

Both parts of the Standard Model got early, dramatic encouragement from the "November Revolution" of 1974, with the discovery of the J/ψ family of particles and the subsequent phenomenology of charmed quarks.

Since then the Standard Model has gone from triumph to triumph. The Cabibbo-Kobayashi-Maskawa theory of CP violation anticipated the existence of a third family - an anticipation eventually fulfilled through discovery of τ leptons and b and t quarks. A very recent triumph was the discovery of the final "missing ingredient" postulated in the model, namely the Higgs particle, whose measured properties so far fit the profile of the simplest, minimal implementation of $SU(2)\times U(1)$ breaking.

Beyond these discrete showpieces, the astonishing precision and scope of the Standard Model, already alluded to, is profoundly impressive. "Analysis and Synthesis" has a firm foundation, adequate both for adventurous applications (e.g. cosmology) and for

supporting further explorations (e.g. neutrino oscillations, proton decay, supersymmetry, axions).

What broader conclusions can we draw? Here are three:

Nature obeys precise mathematical laws.

Reductionism, as a strategy for physics, works.

Special relativity, quantum mechanics, and symmetry rule.