Quantum Theory and the Physics of the Very Small

Waseda University, SILS,
History of Modern Physical Sciences

Fields and Particles

In the late 19th to early 20th century, it seemed like fields had a major role to play in our understanding of nature. Electromagnetism and light were understood as phenomena of the electromagnetic vector field. Einstein recast gravity as taking place within a time-space manifold, mathematically modeled as a tensor field.

Around the same time, however, certain aspects of these phenomena were becoming understood as involving particles – such as cathode rays and the photoelectric effect – which to the development of a new quantum theory. In this way, the development of quantum mechanics, however, lead to recasting many of these theories in terms of a new type of particle.

This has lead to the conception of quantum objects, each with an associated quantum field. Quantum electrodynamics has been very successful, quantum gravitation, less so.

Blackbody, or Cavity, Radiation and Energy Quanta

A blackbody, or cavity, absorbs all electromagnetic radiation of every wavelength, so that when it is heated it should emit all wavelengths. There were significant discrepancies between the predictions based on the assumption of continuous radiation and the experimental values.

This phenomena was studied at the Physikalisch-Technische Reichsanstalt and Max Planck (1858–1947) introduced *energy quanta* – discrete packets of energy – as a purely theoretical device, to explain the experimental values of blackbody radiation.

Using a statistical model that was based on Boltsmann's methods, he modeled the energy of the body as a statistical characteristic of set of unknown "resonators," using $\epsilon = nh\nu$, where $\epsilon :=$ energy, $\nu :=$ frequency of vibration, $h \approx 6.6 \times 10^{-34}\mathrm{J} :=$ Plank's constant, $n := \{0, 1, 2, 3, \ldots\}$. This quantum *discontinuity* – $n := \{0, 1, 2, 3, \ldots\}$ – was at first not considered to be physically important. It was a just a simplifying assumption that produced an accurate radiation law.

Plank's Initial Conception

Plank, Letter to R.W. Wood, 1931

"By then I had been wrestling unsuccessfully for six years with the problem ... and I knew it was of fundamental importance to physics... A theoretical interpretation therefore had to be found at all costs, no matter how high... The new approach was opened to me by maintaining the two laws of thermodynamics... I was ready to sacrifice every one of my previous convictions about physical laws. Boltzmann had shown how thermodynamic equilibrium is established by means of a statistical equilibrium, and if such an approach is applied to the equilibrium between matter and radiation, one finds that the continuous loss of energy into radiation can be prevented by assuming that energy is forced, at the onset, to remain together in certain quanta. This was a purely formal assumption and I did not really give it much thought."

The Photoelectric Effect

In 1905, Einstein published a paper in which he gave a quantum explanation of the photoelectric effect.

The photoelectric effect had been discovered by H. Hertz in 1887, when working on electromagnetic waves – shining high energy light on metals can induce currents. P.E.A. von Lenard (1862–1947) then showed, in 1900, that the when high energy electromagnetic radiation, as light, shines on a metal, electrons are emitted and that the maximum energy of the electrons was independent of the intensity but dependent on the frequency of the light.

Einstein's contribution was an argument that the details of this phenomena could be predicted using an equation that involved Planck's quanta of energy radiation, now assumed to be particles of light, and again used Planck's constant, h, and provided another way in which it could be determined.

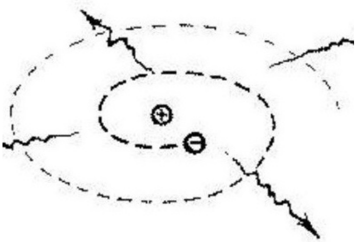
Niels Bohr (1885-1962)

Bohr was born into Dutch academic family, educated at Copenhagen and did a postdoc with Rutherford in Manchester University. He became Professor of Physics at Copenhagen, then director of the Institute for Theoretical Physics.

He developed a quantum theory of the atom, and was a central figure in the rise of the new quantum physics. He wrote prolifically on the philosophical interpretations and implications of quantum theory. He was the most famous advocate of the "Standard (Copenhagen) Interpretation," and argued, especially with Einstein, that quantum objects are non-determinate.

Bohr on G. Gamow's motorcycle, with Gamow behind on Bohr's bicycle

Rutherford's Atomic Theory



Rutherford's atom was a mechanical system like planets in orbit. As the electrons orbited the nucleus they would radiate electromagnetic energy, and should lose speed and eventually collapse into the nucleus. Moreover, they should radiate energy at continuously varying frequencies.

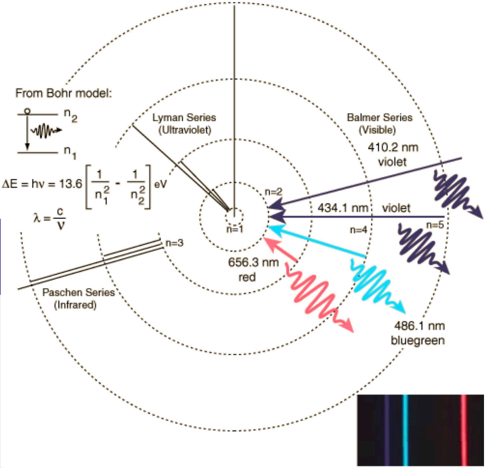
Bohr realized he could use the quanta of Planck and Einstein to stabilize these orbits. While he was working out these details, a colleague pointed out that his model could also account for spectral lines of chemical elements. In working out the details of this it was necessary to incorporate the theory of relativity.

Bohr's Atomic Model

The electrons orbit around the nucleus only at set intervals. When they are in those positions they obey the laws of *classical mechanics* but when they absorbed or emitted electromagnetic radiation they did so in *quantum jumps*.

Bohr, "On the Constitution…," 1913

"The dynamical equilibrium of the systems in the stationary states is governed by the ordinary laws of mechanics, while those laws do not hold for the transition from one state to another."



Bohr's atomic model

Prediction of the Model

Bohr was able to use his model to give an explanation of the red and bluegreen spectral line for hydrogen. He predicted further lines in the ultraviolet range. These were found the following year. The model, however, indicated that atoms have fundamental behaviors which are unlike anything we encounter with ordinary objects. Both the light and the electrons seem to exhibit some characteristics that are not found in classical objects. Moreover, there seems to be no way to visualize the actual structure of these atoms.

Bohr, Letter to Heisenberg

"There can be no descriptive account of the structure of the atom; all such accounts must necessarily be based on classical concepts which no longer apply… For we intend to say something about the structure of the atom but lack a language in which to make ourselves understood… In this sort of situation, a theory cannot 'explain' anything in the strict scientific sense of the word. All it can hope to do is reveal connections and … leave us to grope as best we can."

Quantum Objects

Quantum objects, like electrons, photons and all subatomic particles, have characteristic behaviors that we could not predict by studying the macroscopic world around us. Nevertheless, the phenomena characteristic of quantum objects can be determined through experiment, and are reproducible.

- Particle like behavior: under some circumstances, quantum objects do things that are similar to particles.
- Wave like behavior: under other circumstances they do thing like waves, and exhibit behavior characteristics of a field.
- Indeterminate behavior: some things about quantum particles are indeterminate, but not totally random – decay time, position and momentum, undetected path, interaction with a detector, and so on.

The Early Development of Quantum Mechanics

Quantum mechanics was developed over a number of years by many physicists – such as Bohr, Max Born (1882–1970), Werner Heisenberg (1901–1976), Wolfgang Pauli (1900–1958), Erwin Schrödinger (1887–1961), Paul Dirac (1902–1984), and others.

The theories are composed of mathematical principles and rules that apply to quantum objects. For example, Heisenberg produced a theory based on metric mechanics, while Schrödinger produce another based on wave functions – both are abstract theories that formulate the quantum behavior of sub-atomic processes through mathematical models that can be used to predict the probabilities of various experimental outcomes. Subsequently, Dirac showed that these two theories were mathematically equivalent. (Another equivalent theory was later formulated by David Bohm (1917–1992).)

Bohr, Heisenberg, Pauli, and others, argued that these mathematical rules are the only understanding we will ever have – that the underlying structure can never be discovered.

Fundamental Indeterminacy

The statistical path, or *orbital*, of a quantum object can be exhibited with x-ray diffraction, but they were technically difficult to produce.

Schrödinger's wave equations, however, could be used to calculate the probability distributions.

The fundamental particles exhibit either the properties of waves or particles, depending on how they are observed.

Bohr

"Quantum mechanics is about one thing: What can we do with our instruments?"

Although a number of the founders of quantum theory believed that this indeterminacy was something that was true of the quantum objects themselves, others – such as Einstein, Schrödinger, De Broglie and later Bohm – believed that the indeterminacy was simply due to the fact that we do not know all of the variables involved.

The Uncertainty Principle

In 1927, Heisenberg produced an argument that we would never be able to know the full set of variables for quantum objects.

He used a thought experiment involving a "microscope" which measures the position of electrons in atoms by firing photons at them and measuring the reaction. We want to know the position and the momentum of the electron.

When the photon collides with the electron, however, it disturbs it in such a way that we no longer know its momentum precisely. What we know is $\Delta x \cdot \Delta p \geqslant h/4\pi$ – where $\Delta x :=$ change in position, $\Delta p :=$ change in momentum, and $h :=$ Plank's constant.

This means, again, we can only develop a statistical idea of the electron's path. In fact, the more precisely we know the position, the less precisely we know the momentum, and the converse.

The EPR Thought Experiment

In 1932, John von Neumann (1903–1957) produced a mathematical argument that there could be no *hidden variables* in quantum theory – that is, that particles could not have some underlying deterministic plan about how they would behave in certain situations.

Einstein was fundamentally opposed to this increasingly stochastical view of quantum objects. With Boris Podolsky (1896–1966) and Nathan Rosen (1909–1995), he published a paper – known as the EPR paper – in which they made an indirect argument that either quantum objects must have *hidden variables*, or absurd situations would arise. They proposed that if two quanta are emitted from a radioactive source at the same time, so that they are "entangled" and have the same velocity but move in different directions, then the momentum of one could be measured precisely at the same moment that the position of the other was measured. In this way, either the uncertainly principle would be violated, or the act of measuring would have to be "communicated" between the particles.

Quantum Electrodynamics, QED

After the war, physicists could turn their attention back to fundamental theories. Taking up the work of Paul Dirac (1902–1984) on the interactions between electromagnetic radiation and the hydrogen atom, in 1948–51, Julian Schwinger (1918–1994) published a series of papers working out the mathematical details of a theory of quantum electrodynamics, while a similar, and equally mathematically intensive, theory was worked out by Shin'ichiro Tomanaga (1906–1979). Moreover, Richard Feynman (1918–1988) produced a different, and highly original theory of QED. Finally, Freeman Dyson (1923–), a 25yo mathematician with no PhD, showed that these theories were mathematically equivalent.

QED describes all electromagnetic phenomena as interactions of photons and electrons, treated as purely quantum objects. It provides a derivation of Maxwell's equations – along with a number of novel predictions – and reinterprets the electromagnetic field as a quantum field. It led to advances in chemistry and material sciences, molecular biology, solid state physics, computer sciences, and so on.

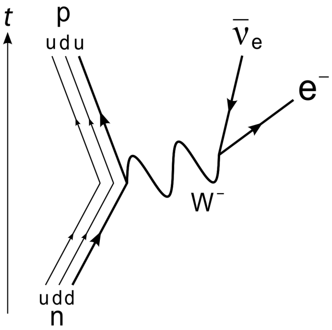
Feynman Diagrams

Quantum interactions are described by complex mathematical models that are difficult even for theoretical physicists to think through.

In order to help make these processes more intuitive, in the course of producing his theory of QED, Feynman developed a system of schematic diagrams that represent various interactions. Following Feynman's lead, other theorists implemented their own systems of diagrams modeled on his, but often visually quite different.

The diagrams themselves can be subjected to various rule-based operations which then correspond to an interaction that may, or may not, occur – depending on other factors, like energy and charge conservation, and so on.

Physicists now use Feynman diagrams as an essential tool for modeling, thinking about, and teaching quantum behavior.

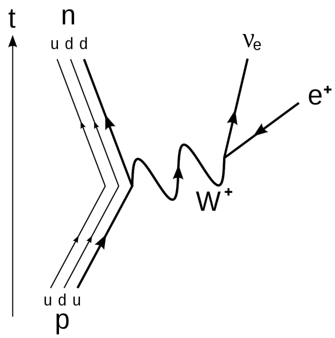


Different types of particles are represented by different types of lines – strait for particles and squiggly for forces. Some particles have charge, represented by an arrow.

We can manipulate the figure in certain prescribed ways, corresponding to underlying equations, to generate new possible events – but they must conserve energy, charge, and so on.

Here we see neutron, n, decay into a proton, p, through the emission of a W^- boson, decaying into an electron, e^- and an electron anti-neutrino, $\bar{\nu}_e$.

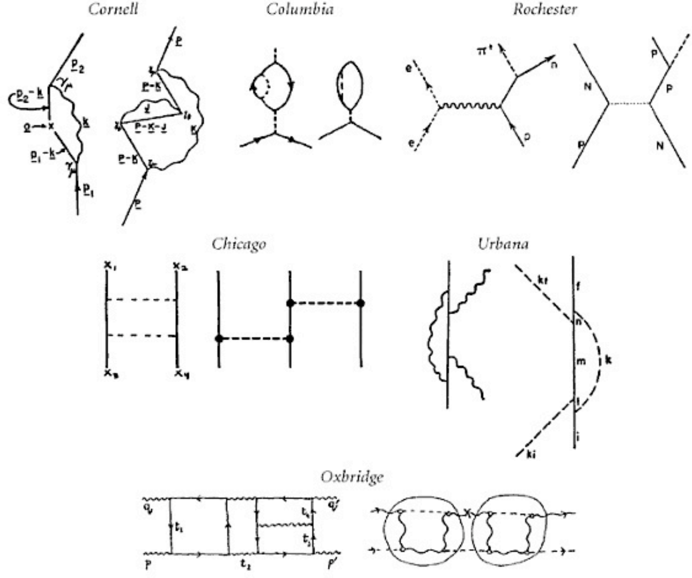
Developing New Understandings



The diagrams also helped physicists think about these events in new ways and develop new interpretations of the processes.

For example, in neutron decay, a neutron is transformed into a proton, emitting an electron and an electron anti-neutrino. On the other hand, in positron emission, an electron neutrino and a positron are emitted, while a proton converts to a neutron.

Looking at the two figures – since the arrows indicate charge – we can think of these as structurally the same process, but orientated the opposite way with respect to time.



Local traditions of Feynman Diagrams

Bell's Theorem

In the 1960s, John Bell (1928–1990) revisited the question of *hidden variables*. He first showed that there was a logical problem in the physical assumptions of von Neumann's argument. He then went on to show that there was a statistically different prediction for the behavior of paired quantum objects when passing through a detector for a hidden variables theory, and for quantum theory.

Specifically, if we measure a quantum property – say spin – for a pair of entangled objects – for example, objects made at the same time in the same process – then it should be possible to describe an experimental set-up in which the predictions of quantum theory were different from the predictions of a hidden variables theory.

That is, he showed for spin, that simply the assumption of a real, hidden property – say up, or down, or rather some plan about what to do under different circumstances – would produce a different predicted outcome than that predicted by quantum theory.

The Implications of the Theorem

From a philosophical perspective, the implications of this theorem is that quantum theory describes a world in which objects either have no real, local properties, such as spin, before they are measured, or if they do then this real property is "communicated" to an entangled object instantaneously – in Einstein's words, "spooky action at a distance."

Bell, "On the Einstein Podolsky Rosen Paradox," 1964

"In a theory in which parameters are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. Moreover, the signal involved must propagate instantaneously."

Experimental Tests

In principle, Bell's Theorem provides the basis for a crucial experiment – and this is exactly how he intended it to be read. Although Bell described the situation with the spin of electrons, most experiments have been conducted on polarized photons.

Although Stuart Freedman (1944–2012) and John Clauser (1942–) carried out a test in the early 1970s at Berkeley confirming the violation of Bell's inequality, it was thought to not sufficiently rule out the possibilities for hidden variables. A stronger result was obtained by Alain Aspect (1947–), after correspondence with Clauser and Bell, for his PhD work at d'Orsay. He introduced controls to make sure that his detectors could not be communicating with each other at light speeds.

Over the years, more experiments have been done with further controls to make sure that light-speed communication cannot be taking place. In each case, the outcome of the experiments has been in line with the predictions of quantum theory.

The Rise of Particle Physics

Cosmic radiation was discovered around 1910 by Theodor Wulf (1868–1942) and Victor Hess (1883–1964).

Cloud chambers – consisting of supersaturated water or alcohol vapor – and bubble chambers – of superheated liquid hydrogen – were developed by Charles Wilson (1869–1959) and Donald Glasner (1926–2013). They allowed physicists to visualize and study the paths of subatomic particles, and the results of their collisions with other particles.

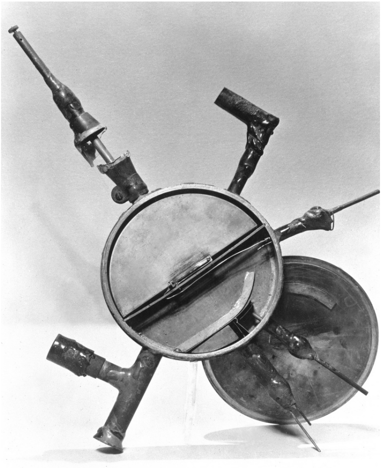
Ernest Lawrence (1901-1958) and his graduate students at Berkeley developed the cyclotron for accelerating alpha particles and other charged particles.

During the World War II most physicists, and most big labs, were occupied with "war work," however, following the war – and now with considerably more expertise in nuclear physics – high energy particle physics became a major field of study.

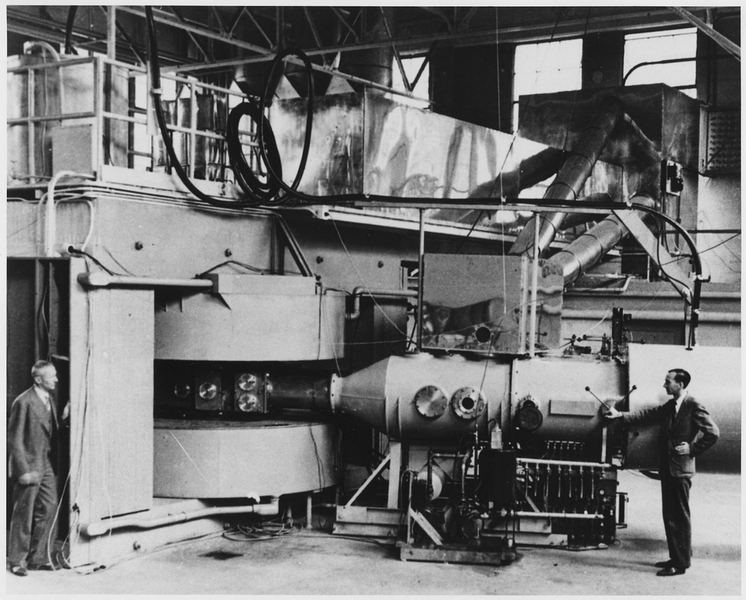
The Cyclotron

One of the first particle accelerators was the cyclotron. By cycling charged particles in a controlled electromagnetic field, they could be sent in a spiral path, increasing velocity, and eventually released into a bubble chamber. In this way, one could study reactions that are much more energetic than those produced by cosmic radiation, or naturally decaying radioactive elements.

In the following years, increasingly larger machines were built to move charged particles at greater and greater speeds.



The first 5-inch cyclotron

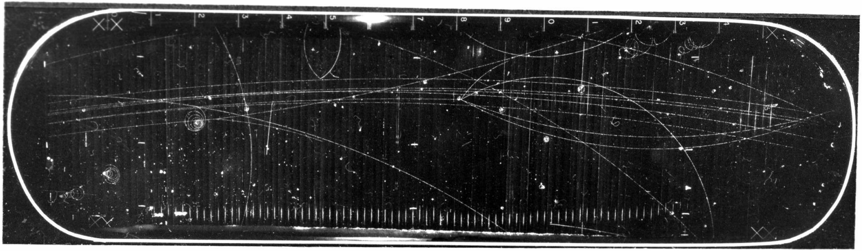


The 60-inch cyclotron, Lawrence Radiation Laboratory, Berkeley, 1930s.

The 4-inch liquid hydrogen bubble chamber at the Lawrence Radiation Laboratory, 1955.

Liquid hydrogen was superheated and pressurized to serve as the bubble chamber.

Tracks in the Bubble Chamber



Photograph of bubble tracks from the 72-inch cyclotron, Lawrence Radiation Laboratory, Berkeley, 1981.

Giant Laboratories

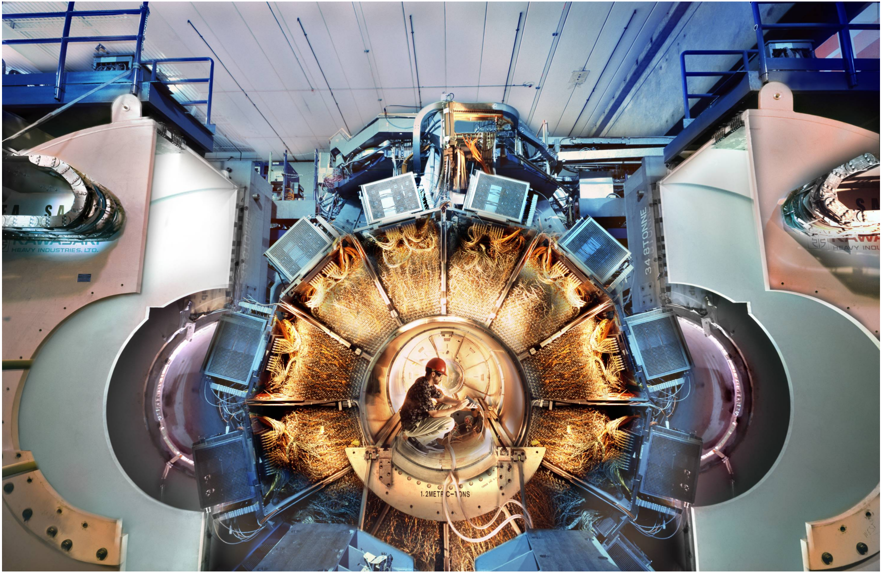
Following World War II, high energy physics was organized on the model of "Big Science" – huge laboratories, large staff, massive budgets, national or international funding, popular exposure with professional public relations departments, and so on. Furthermore, this involved coordination between laboratories and private corporations, as well as intensive collaboration between large teams of scientific and engineering staff.

Some important examples of high energy particle physics laboratories are CERN (from Conseil européen pour la recherche nucléaire) near Geneva, DESY (Deutsches Elektronen-Synchrotron) near Hamburg and Zeuthen, LBL (Lawrence Berkeley Laboratory), Berkeley, Stanford Linear Accelerator Center (SLAC), Stanford, Fermilab near Chicago, BNL (Brookhaven National Laboratory), New York, KEK (高エネルギー加速器研究機構), Ibaraki, and so on.

There are also many smaller labs and hundreds of research groups around the world.

The Stanford Linear Accelerator, established by the US Department of Energy, 1962

The Stanford Linear Accelerator, inside view

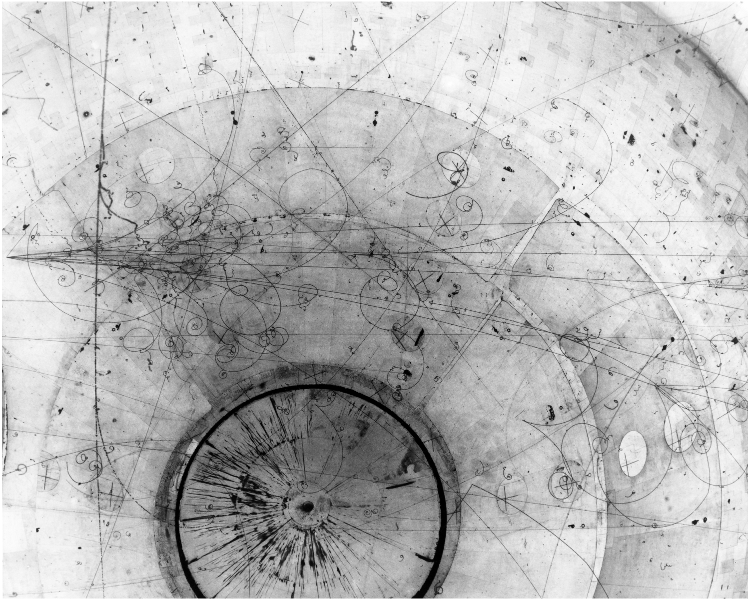


The BaBar detector at the Stanford Linear Accelerator

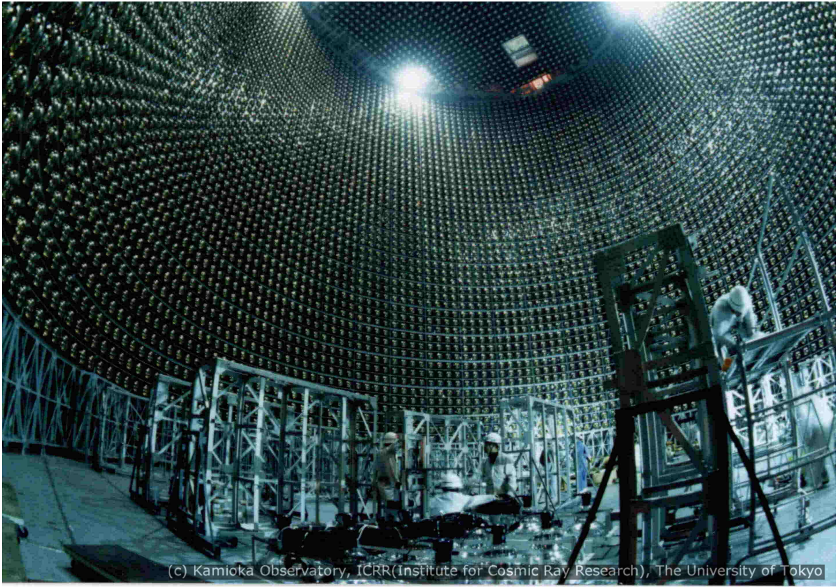
Arial view of Fermilab, established 1967, Batavia, Illinois

The Neutrino Dome, Fermilab, 1972

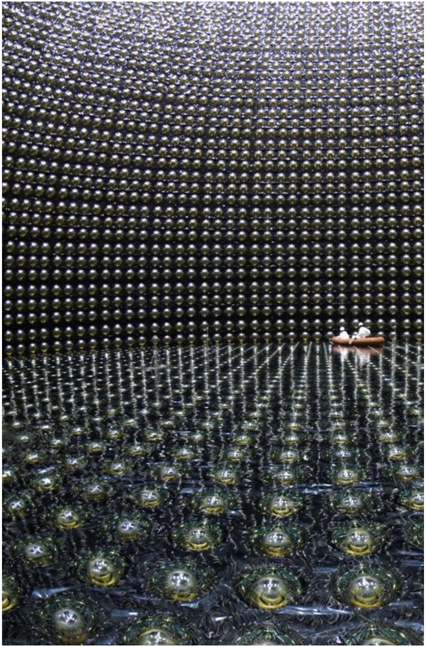
Discontinued bubble chamber at Fermilab, now a sort of sculpture, or monument



Photonegative of bubble-tracks produced in the old bubble chamber



Construction of the Super-Kamiokande neutrino detector, near Hida, Gifu



The Super-Kamiokande was built in in the mid 1990s to replace the Kamiokande detector, which had been built in the mid-1980s.

The Super-K uses ultra pure water to detect the electromagnetic radiation produced when an electron or positron move faster than the *speed of light in water*, following a rare collision with a neutrino.

In the distance we see two individuals in an inflatable boat checking the detector.

Arial view of CERN, established in 1954, with diagraming to show the location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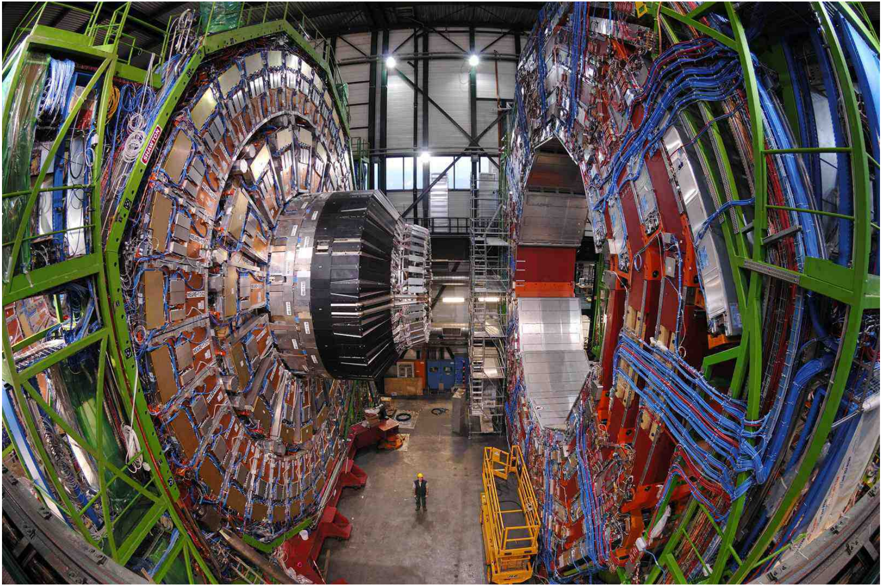
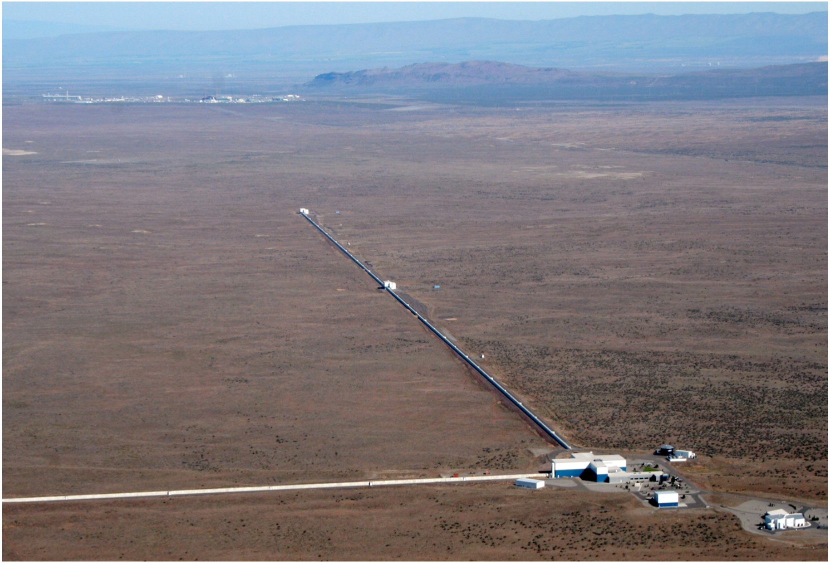


The Large Hadron Collider, ECAL detector, under construction, CERN



LIBO in Hanford, Washington: gravitational wave observatory

Virgo in Pisa, Italy: gravitational wave observatory

The Standard Model

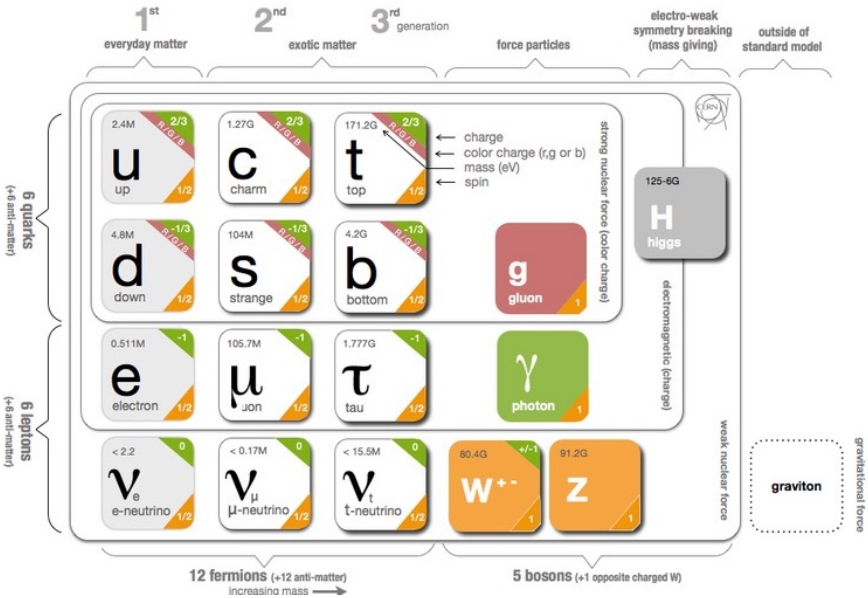
Over the course of some 50 years, hundreds of physicists developed a theoretical model of what is happening in the particle events of the large detectors that is known as the Standard Model.

Many of the particles that are produced in particle collisions are not elementary particles. The Standard Model describes these particles based on more elementary particles.

Like the periodic table, the Standard Model displays patterns among the elementary particles. It differs, however, in that some of the elementary particles do not normally exist in free states, and insofar as it does not have the same degree of predictive power.

There are particles that mostly carry mass, particles that mostly carry force and neutral particles that are very small, or maybe massless, and each is associated with a quantum field.

The Standard Model of Particle Physics



Oveview

20th century, physics become increasingly abstract, mathematical and removed from everyday intuitions.

Quantum theory deals with objects that we never experience directly in their quantum behavior – or at least to the extent that we can recognize it as such – but it has led to many of our modern technologies, such as solid-state physics, structural chemistry, nuclear power. High energy particle physics has yet to produce specific social benefits, but it is important for fundamental physics, cosmology, and so on.

Philosophically, one of the most important results of quantum theory has been the experimental determination that a *hidden variables* theory is incompatible with the empirical basis. This means that – according to the standard interpretation of our current knowledge – we live in a world that fundamentally stochastic.