ITP-2002/32
SPIN-2002/20

THE UNIVERSE OF THE ELEMENTARY PARTICLES

Talk given at CEA Cadarache, France.

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Summary

Hidden inside the nucleus of an atom, there is an entire world of subatomic particles. They are governed by Laws of Physics that display a baffling complexity. But the Universe of stars and galaxies is intimately connected to the Universe of the tiny particles.

July 21, 2004

1. Introduction

The Universe of stars and galaxies can be imagined without too much effort. Powerful telescopes give us pictures of perplexing beauty, and ingenious space vehicles are sent regularly, nearly routinely, to distant planets, moons and comets, showing us their surface features from up close. What these investigations tell us is, first of all, that Laws of Physics hold for these objects, just the same way they hold for us down on the Earth.

They also tell us that the Universe is extremely sparsely populated. Space in the vicinity of the Earth, the Solar System, and our entire Galaxy, is empty. Voids of huge dimensions are surrounding us. Actually, we are fortunate that this is the case, otherwise too many nearby stars and galaxies would heat us up so much that life on Earth would not have been possible, but this does not make these observed facts less amazing.

An atom can conveniently be compared with the Solar System. The atomic nucleus resembles, somewhat, a heavy central Sun, and the electrons orbiting that could be viewed as planets. But there are several very important differences. For instance: the myriads of atoms out of which everything here is made, form only a small set of species, and all members of a given species are *exactly* identical. This does not at all hold for solar systems. And of course solar systems contain not only planets but also moons, comets and other objects, that do not have their likes in an atom.

Just like solar systems, which are controlled by Newton's Law of the Gravitational force, atoms are controlled by Laws of Physics as well, and many of these Laws are quite a bit more difficult for us to understand than those of the planets.

2. The Early Days of Particle Physics

Developments in the physics of sub-atomic phenomena are very fast. The facts that were new when I began my studies in particle physics, are already ancient history by now. The most stable particles known around that time are listed in Figure 1.

Extensive research, using gigantic particle accelerators such as the one at the European Center of (Sub)Nuclear Research, CERN, had provided us with copious amounts of information concerning their nature, but in spite of that, we did not have a theory for the way they interact. What was understood is that various, apparently quite different, forces can act between these particles:

2.1. The Electro Magnetic force

This force was relatively well-understood. Particles carry electric charges, and these generate forces which are transmitted by photons, the quantized energy packets of electric and magnetic fields. These fields are described by Maxwell's equations, more than a century earlier. Extremely precise calculations of the electro magnetic effects on particles were possible for some special cases, such as the calculation of the magnetic moment of particles such as the electron.

2.2. The Strong Force

The details of this force were not understood at all, except that these forces obey laws of symmetry. What this means here is: if you know how the force acts on one particle, the strong force for other particles can be deduced. The force is very strong, but it acts only at distances shorter than the diameter of an atomic nucleus.

2.3. The Weak Force

This was known to be a residual force that can only be revealed in as far as it violates the symmetry constraints of the strong and the electro magnetic forces. Actually, we were not sure at all whether there exists only one weak force or whether there are many kinds of weak force. They could be characterized as feeble asymmetric residual effects after having accounted for the symmetric effects from the stronger forces. The weak forces had been measured in quite a bit of detail, but an accurate theoretical description did not yet exist.

3. The Yang-Mills fields

Yet the seeds for further progress had already been planted. In 1954, a brilliant suggestion had been put forward by C. N. Yang and his collaborator R. L. Mills. The idea was to generalize the successful theory of electro magnetism. They succeeded in writing down equations for a field system that resembles the electro magnetic field, except that particles traversing this field could undergo transformations into other, related particles. Yang and Mills suggested that protons and neutrons may be transformed into one another, or, for example, one kind of pion could be transformed into another kind of pion.

In this respect it is important to mention that sub-atomic particles, just like larger material objects, may have *spin*, *i.e.*, they can rotate about an axis of rotation. Particles traversing a Yang-Mills field must, in general, keep their sense of rotation, but the transitions they can undergo may depend on how they rotate. The total amount of spin, which is zero for the pions, one-half for protons, neutrons and electrons, and one for the energy quanta of the Yang Mills fields fields themselves (called *gauge bosons*), must stay the same.

Unfortunately, this proposal by Yang and Mills did not appear to be very realistic. The problem was that the energy quanta of this field were predicted to be particles just like the photon, the energy quantum of light, but, unlike the familiar photons, these particles should also carry electric charge. Now such particles could not possibly exist. Photons would propagate with the speed of light, which implies that they carry no intrinsic mass; if very light charged particles existed, certainly if massless charged particles existed, they would be copiously produced in electro magnetic fields. The only particles produced in electro magnetic fields are the electrons, which carry a mass of 511 keV; that must be the lightest mass for any charged particle. What was really needed was a theory for particles resembling charged photons, but which carry a quite considerable amount of mass, preferably many times more than the proton. Such particles could well explain some characteristics of the weak force, but they were not predicted by the Yang-Mills scheme.

Even though the correct way to address this mystery had been put forward, by the Belgian F. Englert, the American R. Brout and the Scot P. Higgs, in the early '60s, most investigators continued to search in wrong directions. Looking back, blessed with hindsight, this is an easy thing to say, but in fact this just illustrates how difficult it is to follow the paths of Nature in this alien world. The correct scheme for the weak interactions in the *leptonic sector* of the elementary particles had already been written down, independently, by A. Salam (in a formal sense), by S.L. Glashow (in an approximate sense), and by S. Weinberg (who also had the details right, but he could not describe how exactly to proceed with the calculations). And yet this alley was not followed up immediately. To be able to do this, we first had to clean up quite a bit of mathematical intricacies.

These three men realized how to exploit the mathematical properties of the Yang-Mills field such that one can understand a peculiar asymmetry of the weak interaction: it distinguishes between left and right. We say that particles rotating to the left (with respect to the direction of propagation) can undergo transitions, but particles rotating to the right cannot (for *anti*-particles, it is the other way around). If we allow for *two* neutral Yang-Mills photons, one of which being the familiar photon, and the other one a heavy version, we can let the Brout-Englert-Higgs-Kibble mechanism work. Weinberg wrote down the details for the leptonic particles, but could not get the picture for the hadronic particles such that they interact exactly the way observed in experiments. The leptonic particles are the ones that are insensitive to the strong force. Indeed, to describe hadrons correctly, more needed to be worked out, not only concerning the strong forces that act on these particles, but, as it turned out, not yet all strongly interacting particles were known.

4. The Strong Interaction

Murray Gell-Mann had noticed that the strongly interacting particles appear to behave as composites: the baryons appear to consist of three sub-units, which he called *quarks*, and the mesons appear to be composed of a quark and an antiquark. Assuming the existence of three different species of quarks, he could qualitatively understand many of the observed features of the hadrons.

A major difficulty with this theory was that it did not reveal the nature of the force that would keep the quarks together as described: either three to form a baryon, or one quark and an anti-quark to form a meson. Furthermore, when Weinberg attempted to describe the *weak* force as it acts on the quarks, he hit upon direct contradictions with what was actually observed in experiment.

To get their weak interactions right, the existence of a fourth species of quark had to be assumed. This was first realized by Glashow together with J. Iliopoulos and G. Maiani at CERN. They gave the fourth quark the name "charm". This fourth quark enhanced the symmetry of the quark system just in such a way that the difficulties, in particular regarding the K particles, disappeared.

However, what force is it that can keep the quarks permanently together in grouplets of two or three? The answer turned out, again, to be a Yang-Mills theory. This time, however, one had to attach to the quarks an “internal” quantum property, which was named “color”. Color can take three values: “red”, “green” or “blue”. A quark (or a gluon, the quantum of the strong force field itself), can change color when traversing a Yang-Mills color field. It took us quite a while to understand the detailed consequences of the Yang-Mills equations for the color field. The difficulty here is that their non-linearity is essential, and exact mathematical treatment is almost impossible; a lot of physical intuition was needed to figure out how these fields work. Presently, we understand very well how they work.

The weak force changes the species of the quark into another one; the strong force only affects its color. Together, these forces account for almost everything we see.

Nevertheless, a very slight discrepancy remained. The theory would predict that particles rotating to the left behave *exactly* as antiparticles rotating to the right, and *vice versa*. However, very rare events were observed where this symmetry, called CP symmetry, is broken. The most elegant way to account for this is by assuming yet two more quark species to exist. Once you assume *that*, you must also assume that two more leptons exist, a charged one and an associated neutrino species. This new lepton was also found, and today we believe that also various signals of the existence of the associated neutrino have been picked up.

Thus, we now believe that *six* quark species exist, and three charged and three neutral leptons.

5. The Standard Model

We now arrived at a fairly accurate *model* for all particles and forces known. This happened around 1975. At first it was assumed to be just that: a model. A model is usually understood to be some idealization of reality, a simplification, to be used as a toy to learn to appreciate certain aspects of this world, whose full complexity surely has to involve details not yet fully incorporated in the model. Much to our surprise, however, the model turned out to work so well that, up to the present, practically no deviations from its predictions have been observed. It is true that some minor refinements and adjustments had to be added later, such as the masses and mixing properties of the neutrinos, which had long been suspected to exist, but were confirmed only late in the ’90s.

The accurate agreements between even the earlier versions of the Model with observations was fascinating. It could be established that the number of quarks and leptons is probably not more than six. , that is, the number of *light* neutrinos is definitely equal to three, as could be measured at CERN. Precision experiments and measurements practically excluded the existence of more quark and lepton species. Thus, the Model must have some absolute truth in it.

The comparison between theory and experiment is illustrated in Figure 3, a compilation of experimental data from several laboratories where cross sections of particles have been measured at various energies. The solid curves represent the theoretical calculations, and the dots show the experimental measurements, with error bars. Although the theory does have a few adjustable physical parameters that must be matched against the experimental data, allowing us to shift the curves somewhat, there have been numerous other experiments as well, by which these adjustable parameters could be determined independently, so that actually there was not at all much space for maneuvering the curves to make them fit.

6. The Great Desert

Thus, research of the subatomic particles has revealed in great detail the Laws of Physics that control this sub-atomic Universe. The Standard Model represents this Universe in great detail. Yet it is known that the Standard Model does not represent the *absolute* truth; there are various arguments for this. First of all, the model is not impeccable from a mathematical point of view. We can use it to calculate accurately what happens when particles collide, but not with *infinite* accuracy: there is a limit to the accuracy that can be reached; if we want to cross this limit, the model becomes inconsistent. Actually, it turns out that Nature chose the parameters in such a way that the margins of error are extremely small, in most cases.

Secondly, we know that the model does *not* include everything: the gravitational force has been omitted. We know how to deal with the gravitational force, to some extent, but here the shortcomings of our present theory are the most salient. The gravitational force, when it acts between two elementary particles, is so tremendously weak that we have no way to measure it, and furthermore, it is basically known. The only thing not known is what happens in the domain of physics where the gravitational force becomes strong. And we cannot do experiments in that domain either, because it is where the kinetic energies of elementary particles would reach the *Planck value*, somewhere around 10^{19} GeV. This is many orders of magnitude beyond what can be reached in modern machines. Nature itself can produce extremely energetic particles in catastrophic events far away in the Cosmos, and occasionally, particles from such events reach the Earth, leaving violent tracks in our atmosphere. But even these particles are not sufficiently energetic to reveal deeper secrets concerning the gravitational force.

A third consideration, however, may be more relevant from an experimental point of view. If particles collide at energies just a bit beyond what has been achieved in present day machines, the Standard Model still gives accurate predictions, but we do not believe them. The point is that in this domain of Physics the freely adjustable parameters of the model have to be *fine tuned*. If any of these parameters, in this domain, would only be slightly different from what they are known to be at present, the masses and coupling strengths would no longer look like in our world. This so called *conspiracy* is difficult to accept, and indeed most researchers consider it far more likely that there are missing ingredients in the Standard Model that would cure this apparent disease. There is however no complete agreement about these new ingredients.

A vast domain of "physics" is stretching between the reach of present day machines and the Planck domain. What happens there, and to what extent presently used analysis is applicable here, we do not know for sure. Because of the sparse knowledge that we have about this region, it is referred to as the "Great Desert", see Figure 4. The known particles are listed below, which is the region below approximately 1000 GeV. The Desert stretches for about 15 orders of magnitude.

7. Information from the Universe of the Large about the Universe of the Small, and *vice versa.*

Yet we do want to know what this hidden sector of the subatomic universe is like. One reason for this wish is that the *history of the early universe* must have been determined by these hidden laws. A rough outline of what this history may have looked like is sketched in Figure 5. Reasoning backwards, we suspect that the universe began with a "Big Bang", where particles were infinitely close together and were infinitely hot. The universe grew as it cooled, and eventually matter condensed into the galaxies and stars that astronomers see today in their telescopes. Our picture is reasonably accurate and reliable from the point where the average energies of the particles were in the domain where we trust the Standard Model, which is about 100 GeV. The Universe was not more than one ten-billionth of a second old.

From there, we can attempt to go to the very beginning, and while on our way, we may guess our way through unknown Laws of Physics, to determine what the most plausible scenario must be for the Universe to grow into what we see today. Actually, the amount of data is so large, that interesting constraints can be derived, and we can put some flags into the Desert.

The most conspicuous feauture is the *size* of the present Universe. The second column in Figure 5 shows how that part of the Universe grew that we can investigate at present through ordinary telescopes, being about 10^{10} light years across. At the time where particles had energies around 100 GeV, this part of the Universe was about as large as the present Earth's orbit around the Sun. Now this is much *larger* than the distance light can have traveled during the young age of this Universe. How could the Universe have grown so large in so short a time?

This is a great mystery, because ordinary matter cannot produce the right kind of forces that can have caused such a growth. We *can* imagine totally different forms of matter with properties such that, when plugged into Einstein's equations of the gravitational force, *does* cause a tremendous growth.

So, it is generally assumed that when ordinary matter is compressed way beyond the compression values that can be understood in Standard Model Physics, it may undergo essential changes into this kind of super matter. Paradoxically, this super matter is required to feature an enormous amount of *negative pressure.* Due to this negative pressure, the initial explosion of the universe was enormously energetic, causing the Universe to expand *exponentially.* We call this the "inflationary universe". The idea was first put forward by Alan Guth, but later refined by many others.

It is a fortunate circumstance that this theory can be put to a test. During the initial phases the universe is "predicted" to have been so tiny that the tiny *quantum fluctuations* that occurred at that time, resulted into colossal distributions of matter at later times. These distributions presently form gigantic clusters of galaxies! What is also important to us is that the quantum fluctuations of the Universe caused small ripples in the distribution of its gravitational fields, and this in turn affected the radiation that was produced by the hot particles in the Universe. This radiation was in equilibrium with the matter inhomogenuities, but eventually decoupled, when the Universe was about 300 000 years old. Today, physicists are able to detect and study these fluctuations. They are extremely tenuous now, but nevertheless they are standing out against the background of the nearby stars and galaxies. Figure 6 shows one of the most detailed registrations of the "background microwave fluctuations in a part of the Universe, as registered from a balloon that was sent up in the stratosphere above Antarctica. Subsequently, the intensity of these fluctuations as a function of inverse angular sizes was plotted and compared to the theory (see Figure 7). It appears that the theoretical predictions make some sense.

It is here that the Universe of the very largest structures known to exist, coalesces with the Universe of the very tiniest structures that we can speculate about. And, as this branch of Science is still very young, there will be much more to be discovered. Eventually, of course, we hope that the two ends will meet completely, and that we will gain much more understanding about the very beginning of this Universe, and the creation of all matter in it, and that we will be able to fathom the immensely complex Laws governing this world.