The Universe inside the Atom
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Gerard 't Hooft

Gabriel C. Drummond-Cole

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[It's going to get hot in here if we don't get started. Thanks for coming. I'm the director for the Yang Institute. One of the people who has come over the years to the Institute is our speaker today. He came here when Yang was director. We're delighted he still wants to come to Stony Brook. It's a pleasure to welcome our friends downstairs from the math department and from elsewhere on and off campus. Gerard is a Nobel prizewinner and is here from the University of Utrecht. The Renormalization of spontaneously broken Yang Mills theory is only part of his ouevre. I first became familiar with his work in 1974, and in some sense I'm still working out what I learned back then. Others are still working out other things that he first worked on in disparate fields. Today he'll be giving a more general lecture. Welcome, Gerard, it's a pleasure to have you.]

It's a great pleasure for me to be in this university again. Can everybody hear me? We see so often these days pictures astronomers give us from the outer universe. I want to explain other universes, the universes inside the atom, which show as much structure and complexity as the large universe.

Once upon a time there was a point, and the point exploded, and that gave the beginning of the entire universe. The beginning is very difficult for the scientists to figure out, but the first real picture was taken hundreds of thousands of years later. You can see here a completely homogeneous picture of the universe with microwave light. You have to enhance the contrast by a factor of a million to get these blotches of color, which became galaxies. A few billion years later you get this picture from Hubble, of young galaxies only a billion or so years old. This universe is striking because it is controlled by the laws of physics. These seem to be the same everywhere else in the universe as far as we know it. That is a very striking thing. Planets move in basically elliptical orbit around a central mass, like the sun if it's heavier. They move faster close to the sun and a little slower further away.

Another important characteristic of the universe is that it is empty. There's a lot of space between the stars and planets. I want to say that inside the atom there is a similar universe. There is a central unit called the nucleus with electrons moving around it in elliptical orbits.

This picture is a lie. The forces acting on the electron, you might thing, are just like those acting on planets, but the laws of dynamics for these electrons are quite a bit more complicated. The actual way in which electrons move is dictated by quantum mechanics, which are probabilistic and difficult to control. A better picture would make these look like they're out of control. But a closer look says that there are points where these never come and others where they come quite often. By having electrons come more often one place than another you get certain effects, which we call the laws of chemistry. But this is still a very poor model, the real laws of quantum mechanics are much more complex.

Interesting as the universe is, I want to concentrate on the nucleus at the center. If you look at the atom, the atom is much emptier than the universe. electrons are maybe an angstrom from the nucleus, but the nucleus is a hundred thousandth this distance in diameter, compared to a hundredth factor in the solar system.

So I want to focus on the nucleus, made up of the two nucleons, protons and neutrons. A thing I'll say much more about later, each is made up of three subunits, called quarks, and the study of these quarks has become a very important subject in the latter half of the twentieth century and continuing to today.

Now let me stop for a moment in 1969. I was just begininning my graduate studies and I wanted to understand what particles we had in nature. We have species and subspecies, and you give them names and species and so on. So these came in two categories, Leptons and Hadrons, with photons as something on their own. The Leptons were electrons and muons e^- and μ^- and the neutrinos ν_e and ν_μ. Then Hadrons were broken up into different types, mesons and baryons with their subcategories. Hadrons were spin 0, π^+, π^-, π^0, and then $K^\pm, K_L, K_S$, and η, and the spin 1/2 baryons P^+, N and Λ and $\Sigma^\pm, \Sigma^0$ and then Ξ^0, Ξ^- and the spin 3/2 Ω^-. These all had anti-particles except for mesons and photons which were their own antiparticles. There were also excited versions of these.

These were studies later with particle accelerators, like CERN LEP and LHC. This is a landscape between France and Switzerland. This is nearly perfect circle of more than 26 kilometer circumfrence, the inside of which is made a vacuum, and very strong magnets. Particles are made in these tunnels moving in various directions, and they collide; these machines have different names. The last ten or twenty years this was LEP, large electron and proton. The new one is LHC, which will start in 2007. Why such big machines? There we see some of the magnets they're going to put in LHC. These have to be put together very precisely. There are thousands of such magnets. Here is another such machine in Brookhaven. We migh ask why these are so large. Here is a picture of a detector at CERN, and it is huge, scaled to these people. Suppose you wanted to catch very tiny particles, so why not make very tiny detectors? You would be wrong. If you want to see something very small, your microscope should be very big. A fly can see much worse than us. It doesn't see the dirt on a window so it bangs into it. If you want to see really tiny things your eye must be very big.

The game we are playing is to see things as small as possible. You find inside the atom, now, forces, which have been studied experimentally. These come in three types, the electromagnetic force, the strong force, and the weak force. You see the electromagnetic force at a large level, and also in the atom. But there are also two others. We didn't know in 1969 that these were the only ones. We thought then that there were many. There was a force inside the nucleus much stronger than the electromagnetic force. The whole nucleus should have blown apart, but it doesn't. That's a much stronger force than the electromagnetic force. If you have more than 100, it starts to fall apart. In studying the electromagnetic force and the strong force it is found that they basically balance out. But there is a very slight asymmyetry which was called the weak force. Some particles feel only the weak force, like neutrinos, for instance. From this description it should be clear that it was not clear whether there was only one weak force or many.

If you go back to 1954, C. N. Yang had studied with Robert Mills, asking a fundamental question which we will rephrase as, knowing the equations for these forces, can you generalize these equations, and could you have a more general force? They found that you can. If you send a particle through a Yang Mills field, it should act like the electromagnetic field, but it should turn a proton to a neutron, or bac. You could send π^- to π^+ or so on. You could generalize a field so that the equations would do this.

There is one thing that you might worry about, which is what happened to electric charge? The answer was also found as part of the theory, which is that the field contains energy packets, called quanta. The field carries energy packets with electrical charge. The charge is modified because it might absorb or admit a charge. When it does that, the particles themselves carry the electrical charge. This phenomenon means that these field equations will be more complicated, and will act on themselves. So the equations became more complicated and interesting to study. Now you could ask, what happened then, did everybody study these? No.

Why? The good news was that Yang Mills theory broke things up into families that looked about right. But their spin was in three diretions. They found three different rotation states. This is part of the solution. They described things in two dimensions, not three, because light works in two dimensions, not three. So these things could split only two ways (three?). But there was a problem with these things moving the speed of light and carrying charge, because that speed means no mass and no mass means no charge. Massless charged particles would be a problem. So most of their colleagues said that they were wrong experimentally. Massless particles have an axis of motion and they can only spin left and right.

A solution came up a few years later. It can be attributed partially to Peter Higgs. This said that these had too much symmetry. When you had symmetry, it dictates that the particles behave very much alike. The symmetry had to be broken. You can write down equations that have left and right different, but you can also say that it is spontaneously broken. A particle likes to roll to the lowest point of a valley, but if you have a hill in the valley, there is an unstable solution which is neither left nor right. This simple example occurs in many places in physics.

You can look at a Mexican hat shape which has an unstable solution at the center, and the stable solution has a degree of freedom moving around the furrow of the hat. When you break the symmetry there is an extra degree of freedom. Now this is the Hiffs degree of freedom.

A. Salam, S.L. Glashow, and St. Weinberg used this to make a new theory, with a new particle, a spinless particle with a third degree of freedom. Independently these three found a way to put this in a model. So in a Yang-Mills field, the spin of a particle stays the same. The rotation of particles has to be taken more carefully. Neutrinos can have spin, but they can only spin in one direction; there is a built-in orientation. When the weak force is looked at this has to be taken into account.

So the half-integral spin leptons were given orientations. The hadrons did not fit into this theory.

So the hadrons were made up of quarks and antiquarks. These were thought of as combinations of two or three quarks out of the set of quarks. There was a mistery about this, why would a quark and an antiquark or only three quarks or three antiquarks come together like this.

The answer again was Yang-Mills theory. A discovery was made that you can attach a property to these quarks, named color. This came in three colors, red, green, and blue. So a u quark changes color going through the Yang-Mills color field, meaning the field, the quanta, carry color and anti-color. So there were eight different species, this generating the forces within the quark. This was thought to generate the analogue of the electromagnetic force, but a strong force was needed too.

Before going into that, we had nine quarks and their antiquarks, the three colors and then the up and down distinction. The weak force worked on up and down, and the strong force acted on color. The suspicion was made that there were more quarks. They added three more types of quarks to up, down, and strange, and the this helped with the hadronic problem. The weak force paired these.

Some of you might ask, are you sure the list stops at six? That could be the case but quite likely it isn't. If you try to add more quarks you get discrepancies with experimental observations.

Now we want to know how force depends on distance. The weak force dampens to zero very quickly, then the electromagnetic, and the strong develops a kind of vortex, which could be predicted by Yang-Mills theory.

The strong force levels off to a constant. The last Nobel prize was awarded for the discovery of something related to this.

How do you study this? Imagine two electrons collide and then you get two quarks? You can't study this, when things collide, you get jets. The quarks neutralize one another, and so you can calculate the process and compare to experimental results and you get remarkable agreement. This added up to a beautiful picture, called the standard model. We have the weak, the strong, and everything controlled by Yang-Mills. This was a model for fundamental interactions. When this was compared with experimental observations, the results came back in complete agreement with this picture. So this is a standard theory, not a model. That having been said, this model can't be exactly right, because of gravity being missing. But gravity can't be added. Many different laboratories did this work, and the measurements, on this graph, are shown to agree very well with this picture. You can't even see the difference on the weak where $e^+e^- \rightsquigarrow \gamma\gamma$. Now LEP has produced further data, with no deviation from the theory.

So the standard model is really the model describing all particles known at present, controlled by the universal laws of physics. There are particles which do not exist in the standard model. There are twenty-six constants of Nature. There used to be twenty-one, when it was found that neutrinos can rotate in the wrong direction. They are extremely inert. So all together 26. Twelve are masses, three coupling strengths, and eleven mixing parameters, and some of these are left-right asymmetric. We know the model is incomplete, because there are particles not in the theory. Mathematically we know that this will explode on itself, it is not entirely consistent. The fourth force, gravity, is extremely weak. This might surprise you. You don't feel other forces, so why do you say this? The atoms are attracted in the same direction toward the earth, while the positive and negative charges balance out. It acts as an accumulative force. To illustrate that its effect is very weak. While you stand on the ground, a layer of molecules on the ground and one in your shoes are stronger than all of the gravitational force. Gravity is very weak. If you go to high energy particles, it becomes very strong. If you to high energy, you get higher mass and you get stronger gravity. We can only get to 10^{-18} meters. Above we have nothing because our accelerators are not powerful enough. This area above is called desert. If we scale everything we know, then at some point, everything becomes equal. Further than that the gravity becomes strong. I should try to reach a conclusion.

There is further unification. $SU(4) \times SU(2) \times SU(2)$ and something about a fourth color. Maybe the picture can be combined to a sixteen-space rectangle. This is mathematically an elegant picture, but this has to be repeated three times to get three generations, $SO(10)$, which has a small subset of this (above) as what we talk about today.

Remember the picture at the beginning, the homogeneous picture of the young universe? The same combinations were there a long long time ago. Then you see the quantum fluctuations of the universe. These theories require other kinds of particles requiring higher energy and bigger accelerators. The theoretical predictions seem to agree with the observations. This was when the universe was too young for the laws of physics to apply. This can only be explored by looking at cosmic radiation and hopefully we will get another picture.

The ultimate atoms will not be particles but strings, but these equations are extremely complicated. This is an extremely complicated and unclear topic. We still don't understand the details of the strings and their responsibility for the actions of the particles. I have come full circle from the extremely small to the extremely large. Thank you.

[A few questions?]

[How does one create a Yang-Mills field?]

The field exists everywhere bit is very weak. These fields do not range outside the nucleus.

[It's a little controversial. Logic and our ability to perceive are suited not for understanding and survival. We discover these asymmetries through applying logic to our perception; is there a problem with that? We will forever, in a causal universe, we will discover recursively ad infinitum something.]

We humans apply human logic which might be very different, but as experiment tells us the universe is accessible to our logic. Our brains have been evolved at being best at shooting bows and arrows but we can understand successfully the universe, seemingly so different from the logic of bows and arrows. My answer is that the arrows follow the same logic as the particles. It is not so different. We are now use our logic to look at particles as at bows and arrows. Logic is logic.

[Experimental validation is built into our logic.]

I understand what you say. We use experiments, then the experiments would not confirm what we are doing. This seems to indicate that there is some sense in what we're doing.

[What do we mean by particle?]

The atom consists of things called particles, that is vague, but when we talk about strings things become more precise. It is a point which carries certain data, mass and spin and so on. These are things that we can't explain before a few years of study of quantum mechanics. These particles are controlled by laws, with dynamics controlled by quantum mechanics. A particle is a description of what we see. We can rephrase it as a quanta of energy, and strange and paradoxically enough, the energy packets are the same as these particles. How can energy packets be particles as well? That is a miracle of the theory. The laws of quantum mechanics are based on that and they work.

[Let's thank our speaker again.]