PONTIFICIA
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COMMENTARII

Vol. III N. 29

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COMMENTARII
Vol. III - N. 29
pag. 1-6

UNDERSTANDING ELEMENTARY PARTICLES BY GAUGE THEORIES

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The physics of matter has proceeded a long way since Galileo Galilei came for the first time to grips with the elementary laws of mechanics, nearly four centuries ago. The first discovery of a force that could be described by a mathematical formula was found by Isaac Newton in 1687: the gravitational force that governs the motion of the earth, the planets and the sun. The next fundamental forces that could be given a mathematical description were electricity and magnetism, by James C. Maxwell in 1873.

To understand other forces among particles of matter two great revolutions had to take place in the thinking of physicists, in the beginning of this century. One was the theory of relativity. Now some of the details of this theory are difficult

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Lecture presented at the Pontifical Academy of Sciences in occasion of the award of the Pius XI Gold Medal, November 12, 1983.

to explain in non-technical terms, but many statements in this theory can be followed and appreciated by many people, also non-insiders, and that is, I think, why this theory caught the imagination of a large, fascinated public. It became symbolic for the abstract mind of a physicist.

Unfortunately the other theory, quantum mechanics, is really only accessible to the experts, but its philosophical implications for science are even more profound. The public only gets some vague notion of "probabilities" and "indeterminacy", a confusing picture of this beautiful framework. For scientists the theory is bewildering, not only for its philosophical implications but also for its absoluteness and its accuracy.

Both relativity theory and the quantum theory seem to be absolutely correct in their predictions to us, but their region of applicability is very different. Quantum mechanics changes the laws of mechanics only when applied to extremely small objects such as atoms or molecules, whenever they exchange only tiny amounts of energy or momentum over small distance and time scales. Relativity holds for any object that gets velocities close to the speed of light such as a spacecraft (manned or unmanned), a planet, or a light-ray. If smaller velocities are involved then the relativistic effects can only be seen by extremely accurate observations.

Clearly one may ask now how to describe the tiniest particles (atoms, nuclei) when they move with speeds close to that of light, for instance when they collide. In that case *both* theories should apply. Apparently, the two theories have domains of applicability that overlap.

Now this is a notoriously difficult situation. We have two sets of laws of nature, looking very different indeed, that *both* have to be obeyed. These particles are not unlike the catholic inhabitants of a country who on the one hand have to obey the laws and regulations issued by their king and government, and on the other hand the laws of the church. In the case of elementary particles, when they have to obey

the laws of both theories at once, their behaviour becomes very complicated to understand. The theory describing these particles is called "quantum field theory". It was found that creation and annihilation of particles had to be taken into account, and the notion of *anti*-particle had to be introduced.

As long as these particles move freely they are easy to describe, but real problems arose whenever any kind of interparticle force was considered in combination with the two doctrines of mechanics, for instance electromagnetism. It is fortunate that the unit of electric charge e for most particles is small when compared with the quantum constant $\hbar$ and the speed of light c. Because of that, a first approximation of the effects of this force could be computed in a satisfactory way. But that approximation could not be exactly right. When higher accuracy was required the theory began to give nonsensical answers: the effects would seem to become "infinitely strong"!

Naturally, many people concluded from such "impossible" answers that theorists were on the wrong track. Fundamentally new ideas would be needed here. However, the many alternative theories that were proposed did not improve our insight. In practice, whenever the infinities were disposed of or hidden then also the good features, namely predictive power, were lost. The best theory was obtained not by closing ones eyes for the infinities but by carefully studying to what extent they were actually harmful, blocking any further understanding. It turned out that in some cases the situation is manageable. Infinities occur when one considers e.g. an electron with a *given* mass and a *given* value of its electric charge and then computes the effects of all forces. Now when one computes the total mass of an electron as would be measured experimentally one finds that it consists of two pieces: the "bare" mass as was given to the electron by decree plus the mass-energy of the surrounding fields. Similarly, the measured value of the electric charge is not the same as the given value, because the surrounding fields screen away part of it. The infinities only occur when one wishes to fix those initial, "bare", quantities first. But actually they are unobservable. We only observe the total mass and total charge. It is only when one insists on separating the "fundamental" quantities from the side-effects that the difficulties arise. The rest of the theory is (apart from some difficulties of different nature) essentially finite.

The nice achievement of the last two decades is now that we learned how to perform this "renormalization programme" in the most general case. We know that of the large varieties of forces and systems considered previously only a limited class of models survives if one insists that the renormalization programme works. The forces must be associated with a "transformation symmetry". They govern the motion of our particles in such a way that essentially all they do is turning particles into other particles (in the case of electricity it is the antiparticles that are involved). The particles that are transformed into each other must be very much alike; in some sense even identical. In many cases the distinction between these particles only comes about when an observer chooses a yardstick (called "gauge") to distinguish them. But in other models one particle type occurs, that is very heavy and not so much affected by the transformations. In that case this particle, called "Higgs particle" can be used as a natural yardstick or gauge to distinguish the other particles. Depending on the way in which those other multiplies of particles interact with the Higgs particles the members of one multiplet can then become very different in appearance. The electron for instance is very different from the neutrino (a very penetrating neutral, massless particle) although they belong to one multiplet, and also the proton now differs from the neutron in having an electric charge.

Gauge theories, as they are now called, were first proposed by C.N. Yang and his student R. Mills in 1954. At that

time they were inspired by the beauty of Einstein's equations for general relativity, where also a gauge principle is involved. So one can say that it was considerations of beauty and elegance that led to these theories. Now I claim that such "esthetic" arguments, though often helpful, inspiring and suggestive, are rarely sufficient to lead the way towards better understanding. Here too, the gauge theories that were born so early, had to wait until some sound, logical requirements forced us to apply them. That was in the early '70s, the work in which I was involved. Nowadays all forces among particles as far as we think we understand them are described by the Yang-Mills equations, in combination with some others. This is to my mind already a profound unification of the forces, perhaps more important than certain detailed questions people ask nowadays, which amount to attempting to put all these equations under one denominator, extending the mathematics in such a way that only one coupling constant would be needed. This would be unification in a more litteral sense but although certain successes of such attempts cannot be denied it seems that nature does not allow us a completely unified description that way. To my mind this form of unification is again based on arguments of esthetics but now the inevitable logical arguments that would insist on such structures are lacking.

The aim of these investigations and the enormous energy spent on them is first of all understanding nature. We saw in the case of quantum mechanics, of relativity theory and the science of astronomy that this understanding also affects our religious standpoints and beliefs. It is a natural interaction between science and religion that, I would expect, will continue. If there are any conflicts then that must only be a superficial appearance. Even if science gives us the ultimate laws of matter, including all matter we humans are made of, then still science cannot control the enormous complexity and vast amount of particles involved (with the exceptions of a few simple statements such as conservation of energy etc.). This complexity of the system of elementary particles that build an entire human being is so far beyond our imagination that it can easily account for the apparently inexplicable intricacies of human interactions. It is here that in my opinion laws of religion can, and should, live side by side with the laws of science.