

Reflections

Elementary Particle Physics – Then and Now

The 1951 Indian Science Congress Presidential address (reproduced in the following pages) by Bhabha can broadly be divided into two parts. In the first, Bhabha talks about the development of modern science, the importance of experiments in arriving at the laws of nature and the question of a final fundamental theory. In the second part, he describes the status of ‘Elementary Particle Physics’ at that time. It may therefore be worthwhile to briefly describe the present situation regarding ‘Elementary Particle Physics’.

In early 1951, one already knew about ten different (so called) elementary particles. Soon hundreds more were discovered. This created a crisis since scientists and philosophers have always been fascinated by the idea that the number of basic constituents of nature should be few. Fortunately this crisis was resolved to some extent in the following decades. The modern picture of the basic constituents and their interactions is described by the so called ‘Standard Model’. There are four basic forces in nature which in the order of decreasing strength are (i) strong interactions (ii) electromagnetic interactions (iii) weak interactions (iv) gravitational interaction. As for the basic constituents, there are six varieties (flavours) of quarks (u,d,s,c,b,t) each coming in three colours; and six leptons ($e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$), plus their anti-particles. Besides, there are twelve gauge bosons, comprising the photon, eight gluons and W^+, W^-, Z^0 . According to the standard model, all quarks and leptons are point objects, with leptons (including the electron) experiencing no strong interactions. On the other hand, the quarks and gluons are coloured objects and are permanently confined inside hadrons and cannot exist as free particles. Further, the electromagnetic and the weak interactions are unified into a single force called the electroweak force. This is reminiscent of the unification of electricity and magnetism by Maxwell.

The standard model, though so successful in explaining all the available experimental data, is unable to answer several basic questions including the mechanism for generating the masses for quarks, leptons and massive gauge bosons. Besides, the unification is only partial in this model. In recent years, a ‘truly unified’ theory called superstring theory has been proposed to unify all the four basic interactions. According to this theory, the basic constituents of nature are not point objects but strings of length 10^{-33} cm. The quarks, leptons and the gauge bosons are merely the different modes of vibration of such strings. The modern unification ideas have brought closer the seemingly contrasting worlds of the very small and the very large. In particular, these ideas hold the promise to explain how the universe evolved after the bigbang, as well as the bigbang singularity itself.

One disturbing aspect of recent theoretical activities is that they are highly speculative, with no experimental data to back them up. It is good to remember Bhabha’s views on this issue. As he rightly emphasises, there may be many logically consistent theories which may nevertheless have nothing to do with the actual structure of the physical world.

Are we close to an ultimate theory of everything (TOE) or as others would like to say, a truly unified theory (TUT) ? Again, let us recall what Bhabha says on this matter. According to him, however great the successes of a theory, unless the success is total and complete, it is always possible that something very important may have slipped through the net.

Finally, it is good to remember the words of Bhabha that only science and technology can solve the immense problems facing India. It may be noted here that Bhabha has included both science and technology. This is very important because in this era of ‘liberalisation’ we think that we only need technology and not science. It would be a grave mistake if we continue to neglect science at the cost of technology. A way must be found so that both can go hand in hand. Only then can this country realise her full potential.

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PRESIDENTIAL ADDRESS

CONGRESS PRESIDENT: DR. H. J. BHABHA, F.R.S.

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The Present Concept of the Physical World.

I express my gratitude to my scientific colleagues from all parts of India for the honour they have done me by electing me to preside over the 38th Session of the Indian Science Congress. A peculiar accident of fate has brought about that the Congress over which I am to preside is being held in this Institute, where I worked for six years from 1940 to 1946 during the period of the last war and I have great pleasure in recording that they were six very happy and fruitful years in my life.

I also wish to express on behalf of all of you, and myself our great appreciation of the fact that our Prime Minister has decided to be present with us on this occasion. That he flew to Bangalore yesterday, and will fly immediately after this meeting to Bombay and thence to England on a mission of prime importance, is a measure of his great personal interest in the development of science in India. Were it not for this, scientific development would receive much less encouragement and support than it does, in spite of the fact that only science and technology can solve the immense problems facing the country, the problems of food shortage, low standard of living and illiteracy.

The multitude and variety of the phenomena of Nature, which still fill us with astonishment, must have bewildered and awed primitive man. It is not strange that he should have sought, on the one hand, to gain some control over them by investing them with anthropomorphic personality which could be influenced by entreaty and prayer, and on the other to alter his immediate physical environment so as to provide some little shelter or margin of safety against the more hostile acts of nature. This urge eventually led to the early civilizations and the later developments following from them. These civilizations depended on a considerable body of practical knowledge acquired empirically, and some highly developed arts and crafts. A few crucial inventions such as that of the horse harness in China, or of the zero in mathematics in India, had a profound influence on their historical development. But with a few notable exceptions, scientific activity in the modern sense did not begin till the Italian renaissance.

Towards the end of the fifteenth century Leonardo da Vinci wrote in one of his manuscripts which is now in the library of the Institut de France (G 96 v),¹

“There is no certainty where one can neither apply any of the mathematical sciences nor any of those which are based on the mathematical sciences.”

1. The Notebooks of Leonardo da Vinci by Edward MacCurdy, Jonathan Cape, London 1945.

2 *Proceedings of the 38th Indian Science Congress, Bangalore, 1951*

This was not the mere expression of a specialist extolling his own subject, and I quote this sentence because it was written by one who is recognised as perhaps the most versatile genius the world has known, one who had a greater mastery of all the various arts and sciences of his time than anyone since. It expresses the new spirit of the times, a spirit which was to lead eventually to that vast development which is modern science and technology. "The mathematical sciences" for Leonardo consisted of what had been handed down of Greek mathematics, while by the sciences based on the mathematical sciences he understood the applications of geometry to optics and mechanics. What Leonardo wished to emphasize, I feel, was that as long as an observation of a natural phenomenon remained couched in qualitative terms it would not be definite enough to build on, and only by introducing accurate measurement and quantitative relations into it could one be certain that it was right or wrong within the limits of accuracy of the measurements. Some four centuries later Lord Kelvin was to say

"When you can measure what you are speaking about and express it in numbers, you know something about it, but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."

Once this general approach received fairly wide acceptance, the development of science in the modern sense was inevitable.

It was found quite soon that certain properties, which could be stated in terms of exact measurement, were common to many objects. In certain cases, therefore, it became possible to state a general property without specifying the particular object to which it belonged. Such general properties could then be regarded as laws or regularities of nature which all objects of a certain type satisfy. One such regularity or law of nature was the one discovered by Archimedes, that the loss in weight of a body immersed in water is equal to the weight of the water displaced. Archimedes was indeed one of the shining forerunners of modern science. It is nevertheless interesting to note that his law is a law in statics. Laws involving the motions of objects were to come much later. An example of a dynamical law is the regularity discovered by Galileo, that all heavy bodies fall the same distance under gravity in a given interval of time irrespective of their weight. Other regularities of the same type, but which involve more complicated relations between the objects, are the three laws of Kepler on the motion of the planets.

It is important to note that laws or regularities of nature of the type just mentioned are merely empirical statements of properties observed to be common to a large number of objects. They are all unconnected with each other. In order to connect up such regularities with each other it may be necessary to formulate certain more abstract principles or postulates from which the various observed regularities can be deduced.

Newton's fundamental laws of motion exemplify this new approach. Consider his first law, which reads²

"Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by a force impressed upon it."

2. Cajori, Newton's Principia—a revision of Motte's translation. University of California Press.



Assuming that we understand intuitively what is meant by rest or uniform motion in a right line, we may well ask ourselves what is meant by an impressed force. If we turn to the definitions which Newton has placed a few pages earlier at the beginning of his *Principia*, we find the answer in Definition IV :

“ An impressed force is an action exerted upon a body, in order to change its state, either of rest, or of uniform motion in a right line.”

Expressed in this way Newton's first law would appear to be a tautology : One states that a condition A exists unless interfered with by the existence of B. While B is defined to be present when the condition A is interfered with. It is not the purpose of this discussion to minimize in any way Newton's achievement which is one of the greatest monuments in the history of science, but to understand the real nature of his laws. Let us assume that force can be defined in some other way than in the above definition so as not to make the first law a tautology. One might then imagine the first law to be a statement which we arrive at from direct observation through some process of induction. For example, in commenting on his first law Newton writes

“ Projectiles continue in their motions, so far as they are not retarded by the resistance of the air, or impelled downwards by the force of gravity. A top, whose parts by their cohesion are continually drawn aside from rectilinear motions, does not cease its rotation, otherwise than as it is retarded by the air. The greater bodies of the planets and comets, meeting with less resistance in freer spaces, preserve their motions both progressive and circular for a much longer time.”

The inference is that one may conclude by induction that if we could take a body into space to a very great distance from all other material bodies then it would either remain at rest or move in uniform motion in a straight line. We know today that such an induction cannot be made, and may indeed not even be true for the actual world. While it is possible mathematically to assume a world in which Newton's laws are strictly true, it is equally possible mathematically to think of worlds in which they are not. This analysis shows us that strictly speaking *Newton's laws of motion and gravitation are abstract mathematical statements which he quite rightly calls axioms*. And if they came to be regarded as objectively true it is because the behaviour of objects which could be deduced from them by mathematical reasoning agreed with our direct observations. For example, one could deduce from Newton's laws the regularity observed by Galileo concerning the fall of bodies, the three regularities observed by Kepler on the motion of the planets, and a host of other phenomena. Quite appropriately, his epoch-making work was called “The Mathematical Principles of Natural Philosophy.”

“ The great importance of the contribution of Newton to the development of physics is that it introduced a new approach into science. It led to the acceptance of the position that the ideas which are to be regarded as fundamental for the understanding of nature are certain abstract concepts or postulates which cannot be proved directly, and not the directly observable regularities of nature which can be deduced from them. This position was accepted because it allows one to order different empirically found regularities of nature into a unified logical scheme which would not otherwise be possible.”³

3. H. J. Bhabha, Presidential Address to the Section of Physics, Indian Science Congress, Calcutta, 1943.

4 *Proceedings of the 38th Indian Science Congress, Bangalore, 1951*

“A consequence of this approach is that any newly discovered fact of nature which does not fit into the existing scheme of physics may necessitate a complete change of the fundamental postulates. Since, however, the old postulates were such that a very large body of observed facts about nature could be deduced from them, it follows that they must still have a restricted validity under certain circumstances, and be deducible as approximations from the new postulates. Although, therefore, every new discovery which does not fit into the old scheme necessitates a complete change of the fundamental postulates, the change is always from a certain set of concepts to a set of more general concepts. As one goes deeper and deeper into the understanding of nature by co-ordinating all the known facts into one scheme by the use of wider concepts as the basic postulates, the old fundamental postulates become, in a sense, a part of the superstructure, taking a place in between the new fundamental concepts and the directly observed regularities of nature.

As an example of this process of generalization of the basic concepts, one may recapitulate the well-known development from the pre-relativity concepts of an absolute space and an absolute time to the more general concept of the unified space-time of the theory of relativity. In pre-relativity physics, in recognition of the arbitrariness of the orientation of the three axes of the frame of reference, the natural laws were formulated so as to be invariant for all rotations of the space axes. Time, on the other hand, was assumed to be absolute and the same for all observers. However, in consequence of the observation that the velocity of light c is the same for all observers in uniform motion relative to each other, the idea of absolute rest has had to be discarded leading to the principle of relativity, which demands that the laws of nature should be so formulated as to have the same form for all observers moving relative to each other with uniform velocity. Stated mathematically, the special theory requires that the fundamental equations shall be invariant for all transformations of the Lorentz group, whereas in pre-relativity physics the laws were only invariant for all transformations of the three dimensional rotation group, which is a subgroup of the Lorentz group.”

The above example also serves to show how the basic concepts of a theory may be radically changed, while still retaining most of the notions of the earlier theory, but recognising them to be of limited validity, true not universally but only in certain circumstances. Thus, the absolute distinction between a time interval and a space interval in pre-relativity physics is replaced in relativity theory by the absolute distinction between time-like and space-like intervals, while the notion of the absoluteness of time of the earlier theory is seen to be approximately correct in the new theory for a group of observers moving relative to each other with velocities small compared with that of light.

A widening of the basic concepts automatically reduces the amount of arbitrariness in the theory. For example, in pre-relativity theory the force between two bodies could be taken to be entirely arbitrary. In relativity theory, on the contrary, the force has necessarily to be conveyed through the medium of a field. The basic differential equations which any field has to satisfy in relativistic theory are drastically restricted in their variety by the same requirement of relativistic invariance, so that there is a very limited freedom in the choice of the form of the force which can be exerted between two particles.



When a science reaches an advanced stage, as physics undoubtedly has today, the facts which can be discovered by direct observation become more and more meagre. We may expect, for example, to be able to discover by experiment the masses of the various types of elementary particles, the different processes which they undergo, their general behaviour in passing through substances of different types and so on. It is, however, inconceivable that an equation like the Dirac equation could be deduced by direct observation in some such way as Maxwell deduced the equations of the electromagnetic field. There is, therefore, no other path open to us but to proceed along the lines I have indicated above. In such an advanced stage however we have certain compensating advantages. We have a number of theories to fall back upon with the knowledge that each correctly describes a large body of experimental evidence in certain circumstances. We can, therefore, attempt to proceed by evolving new theories which reduce to the previously known ones in the circumstances in which the latter are known to be correct. As I have stated on a previous occasion then "The aim of theoretical physics must be to find a complete set of mutually consistent mathematical postulates or axioms from which the properties of nature, meaning thereby the result of every conceivable experiment, can be deduced in the form of a series of theorems. It is, however, necessary in order to achieve the last step of comparing the mathematical statements of the theorems with the results of observation that the basic mathematical postulates must be supplemented by a set of prescriptions about the interpretation of the mathematical formalism. It is clearly not sufficient that the postulates should be consistent and their correctness from the point of view of physics can only be demonstrated by an agreement between the deductions and the results of experiment."⁴

It is most important to distinguish this approach from the one which assumes that one can arrive at the laws of nature by pure thought and epistemological reasoning. The latter approach has neither met with much success, nor proved particularly fruitful in promoting an understanding of the physical world. In our approach, on the contrary, we recognized that it may be possible to build many logically consistent theories which have nevertheless nothing to do with the actual structure of the physical world. Theories in pure mathematics provide many such examples. If any set of axioms or postulates can claim to correspond to reality it is because the deductions from them stand the test of agreeing with the results of experiment.

We must turn now to review the development of our picture of the physical world resulting from recent discoveries. It had already been established by the end of the last century that the multitude of substances in nature are all made up by the chemical combinations of a certain number of basic substances called the chemical elements. The smallest unit of a given chemical element was called an atom. The combinations of these atoms, either of the same element or of different elements gives rise to chemical compounds, which compose the body of all the substances that we meet in nature.

Investigation on the conduction of electricity through gases led Thomson towards the end of the last century to the discovery of the fact that this conduction could be attributed to a particle of negative charge having always the same ratio of charge to mass irrespective of the substance

4. H. J. Bhabha, *Reviews of Modern Physics*, 21; 451, 1949

6 *Proceedings of the 38th Indian Science Congress, Bangalore, 1951*

under investigation. Moreover, this mass was some thousand times smaller than that of a positive ion. Subsequent researches have established the fact that there is a smallest unit of negative electricity, smaller sub-divisions of it not being found in nature, and that all negative electricity appears in integral multiples of this smallest unit, which is now denoted by e . Thus it came to be established that there was a type of particle, called an electron, which always possessed the same negative charge e and the same mass m , which was somehow contained in atoms, and whose behaviour was responsible for the phenomenon of electricity.

Since an atom is an electrically neutral body, it follows that if electrons are contained in it, then it must also contain an equal amount of positive charge. It was not clear at the time how the electrons and the positive charges of electricity were distributed in an atom. For example, were the electrons embedded in a uniform medium of positive electricity, rather like plums in a cake? Or were they like planets revolving round a sun of positive charge? The answer to this important question was furnished by Rutherford in 1911. He showed by a study of the scattering of α particles that the true picture of the atom was to consider it like a solar system in which the electrons move like planets round a heavy centre called the nucleus in which all the positive charge and most of the mass of the atom is concentrated. Since the negative charge inside the atom depended on the number of electrons in it and was an integral multiple of e , the positive charge on the nucleus had likewise to be an integral multiple of e . It was soon established that the number of units of positive charge on the nucleus determined the chemical properties of the atom, and that there were 92 such chemical elements ranging from the lightest, hydrogen, to the heaviest, uranium, with 1 to 92 positive units of charge on the nucleus respectively.

The mass of the nucleus of the lightest element, hydrogen, containing just one unit of positive electricity, was found to be always precisely the same, and some 1840 times the mass of the electron. Since this nucleus of hydrogen never broke up into smaller fragments, it became convenient to regard it as a new type of fundamental entity, a new elementary particle, called a proton.

Further researches showed that the mass of any atom was always almost precisely an integral multiple of the mass of the proton, while its charge was a smaller integral multiple of the charge of the proton. These facts led one at the time to accept a picture of the nucleus which made it appear to be made up of protons and electrons only. The number of protons was sufficient to make up the mass of the nucleus, while a certain number of electrons were added inside the nucleus to neutralize the charge of some of the protons and make the total positive charge equal to the actual charge of the particular nucleus. Thus round about 1930, our picture of the physical world appeared to be remarkably simple. The whole material world was thought of as made up of just two types of elementary particles, protons and electrons. By suitable arrangements of these one built up the atoms of the chemical elements. And from suitable arrangements of the latter every other material thing that was found in nature. Light, or in more general terms, electro-magnetic radiation, or photons, and gravitation, were the only two other physical entities found in nature.

A scientist at that time could have thought, as many did think, that when one knew the mathematical laws governing the behaviour of these four elementary types of physical entities, the protons, electrons, photons



and gravitation, one would know everything of a fundamental nature that there was to know of the physical world, and physics in principle would be a subject which had reached its destination. The subsequent development of the last twenty years shows us how far this belief was from the truth. It shows in a striking manner that however great the successes of a theory, unless this success is complete and total, it is always possible that something very important may have slipped through the net. The apparently small but persistent difficulties or inconsistencies in a theory, or small discrepancies between theory and observation, may be essentially unbridgeable within the framework of the basic concepts of that theory and yield the clue to new ideas.

What were these difficulties of which I have spoken? In order to make a body spin about itself like a top we have to impart to it energy and something called angular momentum. It is found that like electricity, which occurs in nature only in integral multiples of the basic unit e , so angular momentum also occurs only in integral multiples of a basic unit which is just Planck's constant divided by 4π , that is $h/4\pi$. Spectroscopic analysis has shown that the two elementary particles, the proton and the electron, each possesses an intrinsic angular momentum or spin of one unit which arises, so to speak, from its spinning about itself like a top. On the other hand, angular momentum which arises from one body moving bodily round another is always an even integral multiple of the basic unit, that is either zero or two or four etc. times $h/4\pi$. Spectroscopic analysis shows that the spin of a nucleus containing an odd number of heavy particles, that is an odd number of protons in our picture, is always an odd multiple of the basic unit much as if the electrons in the nucleus did not contribute to the spin at all, unlike the electrons outside the nucleus each of which must contribute an odd number of units due to its intrinsic spin and its bodily motion. Secondly, both protons and electrons satisfy a law which the theoretical physicist calls Fermi Dirac statistics. It can be shown then that a nucleus containing an odd number of protons plus electrons must also satisfy the same statistics so that in a molecule composed of two such atoms only certain spectral lines must appear and not others. Experiment again shows that the statistics of such nuclei appear to depend only on the number of heavy particles in the nucleus and not on the total number of protons plus electrons in our picture. In fact all the nuclei seem to behave as if the electrons which were supposed to be in them only manifested their electric charge but neither their spin nor their statistics. A bold attempt to face this difficulty would soon have led one to the view that nuclei were not composed of protons and electrons but rather of protons and some hitherto unknown particle having to a very high degree the same mass as the proton, the same spin and satisfying the same statistics. A particle of this description was discovered by Chadwick in 1931 and was called a neutron. It had to be accepted as a new elementary particle and not a composite structure made up of a proton and an electron for the same reason that prevented us from thinking consistently of the nucleus as being made up of protons and electrons. It immediately led to the acceptance of the picture that all nuclei are composed of only two types of particles, protons and neutron. The number of types of elementary particles was thus increased by one.

The acceptance of the neutron as an elementary particle, however, introduced a new feature into our concept of the elementary particles. For it had been known for a long time that certain nuclei, as for example those of the radio active elements, emit electrons every now and then. One can only



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fit this fact into the picture by assuming that when such an electron is emitted from the nucleus it is in fact newly created in the process and that simultaneously a neutron in the nucleus changes into a proton. Thus we have to admit the possibility that while the elementary particles are not composite, and that as long as they exist they are immutable with absolutely constant properties, nevertheless there are occasions when one or more such particles can disappear altogether with the simultaneous creation of another set. For example, a neutron may disappear and give place to a proton and an electron. Since the neutron, proton and electron all have a spin $\hbar/4\pi$ and the bodily motion of these particles can only contribute an even multiple of $\hbar/4\pi$ the conservation of angular momentum and statistical properties compels us to postulate that there must be yet another elementary particle called, a neutrino by Pauli, which possesses no charge, a mass negligible compared with that of the electron and a spin of one unit ($\hbar/4\pi$).

In 1931, Anderson reported a photograph which seemed to be that of a particle of the same mass as an electron and having one unit of positive instead of negative electric charge. The experimental advance of making the cosmic rays themselves take their own photographs instead of taking photographs at random in a Wilson Chamber then enabled Blackett and Occhialini soon afterwards to discover a new phenomenon called cosmic ray showers. Although cosmic rays are a relatively rare event Blackett and Occhialini showed that very frequently many such rays occurred in a shower and subsequent work has demonstrated that such showers of particles are produced by cosmic rays when they pass through matter, as for example sheets of lead placed in the Wilson Chamber. Blackett and Occhialini showed that their showers contained not only the usual electrons but a comparable number of electrons with the opposite charge. With this, the existence of the positron, as this new particle was called, was established.

The existence of the positron could be understood immediately in terms of an equation for the electron which Dirac had put forward in 1928 and which combined in it for the first time the ideas underlying the theories of relativity and quantum mechanics. Dirac had already shown that certain apparent difficulties in his theory could be understood as expressing on the one hand the existence of a particle of equal but opposite charge to that of the electron and on the other the possibility of a pair of such positive and negative particles being created by the materialization of energy or of their annihilation with the transformation of their mass energy into radiation. Subsequent experiments have fully confirmed the correctness of these basic processes predicted by the theory. Nevertheless, a consequence of this theory was that no electron or photon of even the highest energy could penetrate large amounts of matter, while a growing body of evidence from cosmic ray experiments indicated that particles which looked like electrons did in fact penetrate great thicknesses of matter. Thus, there seemed to be evidence that quantum theory failed for very high energy electrons, while at the same time there was no theory to explain the phenomenon of the cosmic ray showers. It was only when the Cascade Theory put forward by Heitler and the present author showed that the existence of cosmic ray showers and the behaviour of the soft component of cosmic rays in the atmosphere and in dense substances could be explained on the basis of quantum theory was it possible to conclude that the electron-like tracks of particles which did not behave completely like electrons nor like protons must be due to a new type of particle having an intermediate mass. Thus, the existence of a new particle called the meson, with a mass some 204 times that of the electron came to be established in 1938.



A particle with a mass of this order of magnitude had already been envisaged by Yukawa in 1935 in an attempt to explain the short range nature of nuclear forces, that is the forces between two particles in the nucleus of an atom, as for example a proton and a neutron. The observed mesons, therefore, came to be regarded as the agency responsible for nuclear forces, and in accordance with this picture the beta decay was then considered as due to the decay of virtual mesons emitted by nuclei. Research carried out since the end of the war has demonstrated that the picture was again not as simple as it was then supposed to be. Firstly, although the decay of mesons into electrons has been confirmed by experiment, more accurate experiments have shown that the electrons are emitted with a continuous distribution of energies and not with a sharply defined energy as originally supposed. This inevitably leads to the conclusion that in the process of the decay of a meson into an electron not one but two neutral particles must be emitted.

Secondly the identification of the observed cosmic ray mesons with the particles responsible for nuclear forces inevitably requires them to have a strong interaction with nuclei, whereas the mesons observed in cosmic rays were seen to penetrate large amount of matter with but a very weak interaction with nuclei. A serious attempt to face this difficulty might easily have led one to the conclusion that the particles responsible for nuclear forces were not in fact the observed mesons. This conclusion was, however, not accepted until the studies by Powell and his group of the tracks of cosmic ray particles in special photographic plates had shown that there are in fact two types of mesons with two different masses, and that the one type decays into the other with a period of about one hundred millionth part of a second. The two types of mesons are now known as pi and mu mesons respectively. The meson generally seen in cloud chamber photographs are the mu mesons whereas the pi mesons are the ones which are now identified as being responsible for nuclear forces. In accordance with this picture one would have to attribute an even integral spin (in units of $h/4\pi$) to pi-mesons. The mass of pi-mesons, or pions as they are called in short, as determined from a study of the density of the tracks they produce in special photographic plates appears to be in the neighbourhood of 286 times that of the electron.

More recent experiments with the large cyclotron at Berkeley and elsewhere have led to the discovery of yet a new elementary particle a neutral pion, that is a pion with practically the same mass as the charged pion but with no electric charge. Although such a neutral pion interacts strongly with nuclei, nevertheless it cannot be observed directly in a photographic plate or in a cloud chamber due to the fact that it does not possess an electric charge and therefore does not ionize. Despite this, however, it has been possible to ascertain its mass with very great accuracy. The reason is that a neutral pion decays spontaneously in a time of the order of a hundred million millionth part of a second into two gamma rays. Experiments at Berkeley have shown that when a negative pion hits a proton the latter is transformed into a neutron with the emission of a quantum of radiation carrying away the entire mass energy of the pion, that is some 140 million electron volts. But there is another alternative which can result from this collision, namely the conversion of the proton into neutron with the emission of a neutral pion. The neutral pion then decays immediately into two photons with roughly half the energy of the original pion namely seventy million electron volts. However, the neutral pion that is emitted decays while in motion, thus resulting in a certain spread in the energy of the two gamma rays. From this spread one can calculate the kinetic energy of the



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emitted neutral pion and from this again the difference in mass between the neutral and the negative pion. In this way one finds that the mass of a neutral pion is only a few electron masses less than that of a charged pion.

Rossi has shown that in cosmic rays some two-third of the total energy is converted into charged penetrating particles while one-third disappears into neutral charged particles. Since charged pions can have a positive or a negative charge, it follows from this that the interactions of a positive, a negative or a neutral pion with a nucleon are roughly of the same magnitude.

I now come to particles whose existence is highly probably though not absolutely certain. In 1947 Rochester and Butler in Blackett's laboratory reported certain unusual events which they had observed in a Wilson Chamber. They occasionally saw the tracks of charged particles which seemed to show an abrupt change in their direction in the gas of the chamber. They showed that it was difficult to interpret these tracks as due to scattering in the gas for two reasons. Firstly no recoil nucleus in the gas was visible. Secondly it would be difficult to understand why a particle should have such a great likelihood of collision while passing through the rarified medium of a gas and yet pass through dense matter like a lead plate without suffering any collision at all. They put forward the explanation that these forks were due to the spontaneous decay of a charged particle into another charged particle and a neutral one. Experiments at present being carried out at Pic-du-Midi and Jungfraujoch are rapidly producing further evidence that this interpretation is correct. It would be consistent with the present evidence to interpret the charged particle resulting from the decay as a pion. Whether all the original particles are of the same type is not a question that can be answered at present. Most of the particles appear to have a mass in the neighbourhood of 800 times the electron mass. But there is some indication that there may also be particles of this type with masses more than a thousand times that of the electron. Rochester and Butler and more recently Butler and his collaborators have also produced evidence to show that neutral particles of corresponding mass exist which seem to decay into two charged particles in the same way.

Lastly one should mention the case of a particle observed by Powell and his group and called by him a tau meson, which came to the end of its range and emitted three mesons of which one is certainly a pion.

We see now that at least nine different types of elementary physical entities exist in nature, while the existence of two more is almost certain. While experiments may give us information about the masses of these particles, their mutual interactions and the processes in which they take part, it seems inconceivable that an experiment would enable us to deduce directly the mathematical equation describing the behaviour of any such particle. We can only hope to set up the mathematical equations governing the behaviour of these particles by taking as our guides certain well known principles, as for example the principle of relativity and the ideas underlying quantum mechanics. Even such a clearly defined property as the spin of an elementary particle is not something we can hope to measure directly in the case of particles like the meson but must infer it from considerations of the processes in which they take part, by comparing the behaviour of particles of different spins as predicted by theory with the experimental observations.

The circumstance that there are a dozen different types of elementary particles in nature would lead us to expect that there may be many more,



and indeed with our present knowledge we cannot exclude the possibility that there may be an infinite number of them. This does not mean, however, that we shall never be able to obtain a complete description of them all. There are, for example, an infinity of lines in the spectrum of hydrogen and yet we possess today not only a formula which in one neat expression contains the energies of all these lines but also a mathematical theory which allows us to calculate all the stable states of the hydrogen atom, other properties such as the scattering of electrons by atoms, their creation by photons, and even more complicated properties like the nature of the chemical bond between two hydrogen atoms. It is, therefore, quite possible that with increasing knowledge we may be able to find the formula which gives us the masses of all the elementary particles and the general principles which will allow us to deduce the equation satisfied by a particle of any particular mass.

Lorentz at the beginning of this century regarded the charge of an electron as a property of the electron and tried to explain its mass as due to the energy of the electromagnetic field associated with that charge. The idea that the mass of the elementary particle is wholly of field origin has had to be abandoned today because we know a number of elementary particles all having the same electrical charge but different masses. On the other hand one is faced with the fact that whenever the electromagnetic field interacts with any other type of physical entity, be it an electron, a meson or a proton, then the measure of this interaction, namely the charge of the particle, is always the same. From a phenomenological point of view, therefore, we would be more justified today in considering the electric charge e of an elementary particle as a property of the electromagnetic field rather than of the particle, while considering the mass of the particle as an intrinsic property of the particle, unconnected with its interaction with the electromagnetic field. Our approach to this problem today should therefore be just the opposite of that of Lorentz. If the electric charge e is to be considered as a property of the electromagnetic field, as I have suggested, then since the only unit associated with the field in which it could be measured is the square root of Planck's constant multiplied by the velocity of light, we should consider this ratio, or its square e^2/hc to be an intrinsic property of the electromagnetic field. The dimensionless constant e^2/hc would then appear to be a number associated with the electromagnetic field and not a universal constant of nature, of the same status as Planck's constant h or the velocity of light c which enter into the description of other elementary particles.

It is clear that we are now penetrating into a new level of nature which was practically unknown some twenty years ago. I have pointed out earlier that although there may be an infinite number of types of elementary particles nevertheless this fact in itself does not necessarily force the conclusion that we will never be able to describe nature fully or to explain the physical world exhaustively. On the other hand we cannot be certain with our present knowledge that a complete mathematical theory of the physical world can be based upon a finite number of postulates, and if this were not so we would be faced with a situation in which we could never hope to give an exhaustive description of everything there is in nature, but only to extend with the flow of time the region which we had explored and understood.

