A report on what man already knows — and what he is finding out — about the ultimate nature of matter

The Elementary Particles of Matter

by CARL D. ANDERSON

THE IDEA of elementary particles of matter, of small, discrete, indivisible particles out of which all matter in the universe is constituted, is as old as recorded history. The Greeks in their philosophical speculations discussed at length the question of the ultimate nature of matter. They realized that there were only two possible choices open to them; either matter must be thought capable of being divided into smaller and smaller units without end, or else it must consist of small units which are themselves wholly indivisible.

Many of the Greek philosophers experienced a philosophical difficulty in trying to conceive of infinite divisibility, whereas others found it equally difficult to think of a particle as being truly indivisible. The difficulty is closely akin to that which one experiences when contemplating the limits of the universe, and trying to decide in his own mind whether it pleases him more to think of the universe as unbounded and extending to infinity, or to imagine a finite universe with definite bounds, beyond which there is nothing—not even space.

The idea of the existence of indivisible material particles, however, seems to have had the most appeal to the Greeks, and the atomic hypothesis was expounded and developed in the fifth century B.C., chiefly by Thales, Leucippus, and his distinguished pupil Democritus, until in many respects it resembled the views which are held today.

The views of Democritus were prominent for 500 years but began to wane after the beginning of the Christian Era and by about 200 A.D. had almost wholly disappeared from European philosophical thought. The idea of material atoms did not really appear again in Europe until about the middle of the seventeenth century, a time marking the beginning of the great era of scientific experimentation which has continued with an ever increasing tempo up to the present.

During this period, through scientific research based on experimentation, the atomic theory of matter slowly developed. By the beginning of the twentieth century, the concept of the chemical atom had received general acceptance as a theory based on scientific experimentation. The idea of atoms had thus been removed from the realm of philosophical speculation and had become a proved scientific fact. According to this picture all matter, depending upon its nature, consists of a mixture of varying numbers of the 90-odd different chemical atoms. The size, mass, and other properties of most of the chemical atoms had been determined, although not with great precision.

Discovery of first elementary particles

During the time when the chemical atom was being firmly established as a scientific fact, other scientific investigations were succeeding in proving the existence of at least one particle of matter which was more elementary in character than the chemical atoms. In the decade from 1890 to 1900 the discovery of x-rays and radioactivity, and studies of the phenomena associated with the discharge of electricity through gases, soon proved the existence of the *electron,* and showed that the atoms of chemistry must all be considered as complex structures—structures which are themselves built up of particles of a more elementary character.

The electron was distinguished from the other particles previously studied by physicists and chemists in one very important respect. It was established as a unique particle in the sense that all electrons were identical, no matter from what form of matter they were derived. For the first time, then, the presence of a truly elementary particle was revealed to science. It was found always to carry a negative electric charge, and to have a mass about 2,000 times less than the hydrogen atom, the simplest and least massive of all the chemical atoms. The electron immediately took its place as one of the elementary particles common to all forms of matter.

The following thirty years, from 1900 to 1930, were extremely fruitful in furthering our knowledge of the properties of the chemical atoms. The work of Moseley showed that chemical atoms were members of a family, all of them being related to one another in a perfectly definite and simple way. In 1911 the experimental genius of Rutherford in Cambridge, England, proved the existence of the atomic nucleus, and in 1919 he succeeded for the first time in producing an atom of oxygen from the disruption of the nucleus of an atom

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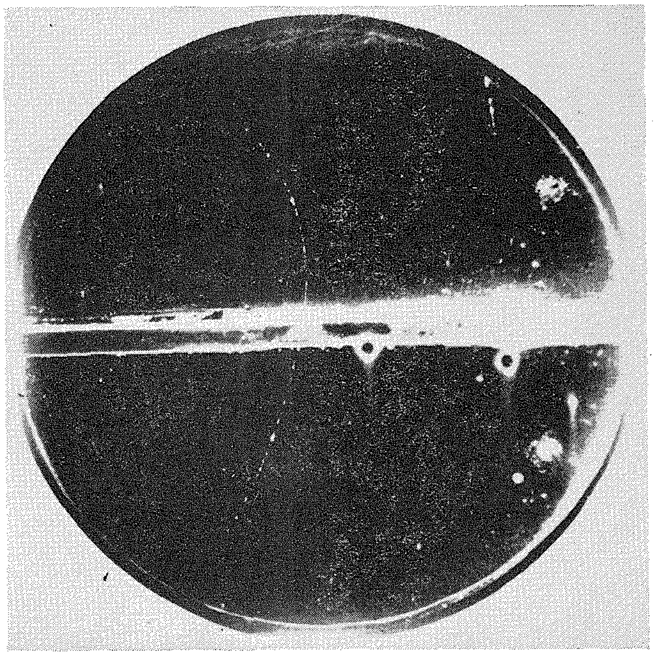


Positron, or positive electron (above), was accidentally discovered in 1932 while cloud-chamber photographs were being made for measurements of cosmic rays.

of nitrogen. Thus in 1919 the will of man for the first time was able to cause the disintegration of an ordinarily stable element, with the accompanying release of nuclear energy. These and other investigations all combined to prove that the *proton*—the nucleus of the hydrogen atom—is a constituent of all other chemical atoms, and hence is in fact one of the elementary particles of matter.

In 1930, then, the physicist had at his disposal two elementary material particles, the electron and the proton, in terms of which to try to understand the structure of all matter. In general he was successful in understanding phenomena which we may classify, for want of a better term, as extra-nuclear phenomena. He was unsuccessful in understanding nuclear phenomena. Extra-nuclear phenomena are those processes in which the electrons which form the outer shells of the atom are the active participating agents. The central core of the atom or the nucleus is present, but remains undisturbed and does not participate actively in the phenomenon. In extra-nuclear phenomena the electron is the active participant; in nuclear phenomena the nucleus is the active participant.

These phenomena have a great many distinguishing characteristics. One of the most interesting and important is concerned with the level of energies involved. Extra-nuclear phenomena involve very low energies as compared with nuclear phenomena. The physicist uses the term electron-volt as a measure of energy. The energies of extra-nuclear phenomena are usually found to range from a fraction of one electron volt to several electron-volts, whereas nuclear phenomena are usually found to correspond to several millions of electron-volts.

In our environment, almost every phenomenon in nature represents an extra-nuclear phenomenon; the burning of coal, the growth of plants, the generation of electric power by conventional means, the fermentation of wine, the explosion of dynamite, and others in uncountable numbers. Nuclear phenomena are not so commonplace, but a few examples are the generation of the sun's heat, the decay of radium, the manufacture of plutonium, the absorption of cosmic rays in the earth's atmosphere, and the explosion of an atom bomb.

The concept of energy has been introduced here because of the great importance that this concept has in the discussion of any physical phenomenon. I have stated that extra-nuclear phenomena represent low energy phenomena and nuclear phenomena represent high energy phenomena. To be more accurate I should have said that in extra-nuclear phenomena we find low *concentration* of energy; that is, the energy changes that one associates with a single elementary particle are low in extra-nuclear phenomena and high in the case of nuclear phenomena. Moreover, physicists for the past several years have been studying certain phenomena which represent energy concentrations many thousands of times greater than those represented even by nuclear phenomena. This has been called the range of *ludicrously* high energies. So far the only opportunity the physicist has had to study phenomena in the range of ludicrously high energies is in connection with observations associated with cosmic rays, but important knowledge of the elementary particles of matter has come from these studies.

By 1930 two elementary particles of matter were known to the physicist. Then suddenly in 1932 two new elementary particles were discovered—the *neutron* and the positive electron, or *positron*. The known elementary particles were therefore doubled in number, increasing from two to four.

The discovery of the neutron, which came as a result of experiments performed in Germany, in France, and in England, was immediately welcomed, for now neutrons together with protons could serve as the building stones for the various types of atomic nuclei. Now it was no longer necessary to assume the existence of electrons *inside* the nucleus, a concept which always had been accompanied by very serious theoretical difficulties.

The discovery of the positive electron, or positron, came during a series of experiments being performed for the purpose of measuring the energies of the particles produced by cosmic rays. It was an unexpected discovery. This statement is true, although about two years before, a British physicist, Dirac, had announced a new theory which actually predicted the existence of positrons. This feature of the theory was not welcomed by physicists, however; on the contrary, it was considered to be an unfortunate defect in the theory and many attempts, by Dirac himself and others, were made to remove it, although all were unsuccessful. If even one physicist had taken the theory seriously, he would have had an admirable guide leading directly to the discovery of the positron. Had this happened, the positron would almost certainly have been discovered by 1930 rather than in 1932. However, after the positron was shown actually to exist, then it was a very short time indeed until many of its properties were understood in terms of the Dirac theory.

The discovery of the positron represented the first instance in which it was recognized that an elementary particle of matter may have only a transitory existence. In ordinary matter, for example, the average life-span of a positron is only a few billionths of a second, for when a positron and a negative electron come close to each other they mutually annihilate each other. The two particles disappear and in their place one finds only radiation; the whole of the material substance constituting the particles is spontaneously transformed into radiant energy. Measurements show that this process is quantitatively in accord with the now famous Einstein equation $E = mc^2$, which relates mass and energy. The process which is the inverse of the annihilation of material particles also occurs—namely, the production of particles out of radiation. If radiation of sufficiently high energy is passed through matter, electrons and positrons are generated. In this process the material substance of the two particles is actually created out of the energy represented by the radiation, and again in conformity with the Einstein equation $E = mc^2$.

In the light of these happenings one must change his concept basically of the elementary particles of matter. These particles are no longer to be thought of as permanent objects which always preserve their identity, and which serve only as building blocks of matter by joining together in groups to form the more complex chemical atoms. One must recognize instead the possibility of the creation of material particles out of radiation, and the annihilation of material particles through the production of radiation. Such a possibility, of course, was completely inconceivable to the Greeks in their long philosophical discussions on the indivisibility versus the divisibility of matter.

The mesotron

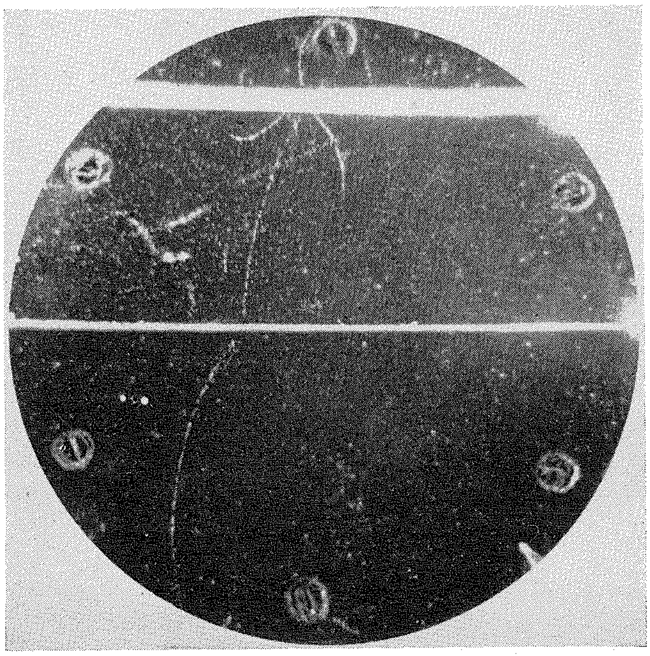
A further step toward a realization of the great complexity inherent in the relationships among the elementary particles of matter came in 1935 with the discovery of the *positive* and *negative mesotrons* or *mesons*, as they are often called. This discovery was also made in investigations of the high energy phenomena occurring when cosmic rays are absorbed in their passage through matter.

The mesotron is a particle some two hundred times as massive as an electron, and therefore about one-tenth as massive as either a proton or a neutron. It occurs with both positive and negative electric charge. The discovery of the mesotron did not come quickly and accidentally, as was the case with the positron and the neutron. It came only after the completion of a sustained series of observations covering a period of four years, which were designed to remove certain inconsistencies always present when we attempted to understand certain cosmic ray phenomena in terms of the elementary particles then known. These inconsistencies were removed in terms of the existence of the mesotron, whose discovery was publicly announced in 1936.

Unlike the neutron, the mesotron was not a particle to be immediately welcomed by the physicist. The physicist makes his advances by simplifying his understanding of nature; hence a physical world which could be explained in terms of only one or two distinct elementary particles would be most to his liking. The discovery of the mesotron did not introduce a simplification; rather, it complicated the situation, for it increased the number of material elementary particles from four to six. Apparently the Creator does not favor a world of too great simplicity.

Before the discovery of the mesotron a Japanese physicist, Yukawa, had postulated, on theoretical grounds, the possible existence of particles of a mass intermediate between a proton and an electron. His theory, however, was not generally known to physicists at that time, and did not have any part at all in the discovery of the mesotron. Had this theory been generally known, it is still doubtful if it would have affected the course of cosmic-ray research. Unlike the Dirac theory of the positron, it would not have served as so useful a guide for the research to follow.

Like the positron, the mesotron has a very short life-expectancy. In free space, both positive and negative mesotrons have a normal life-span of just over two millionths of a second, after which time they spontaneously disintegrate. Very recent observations have shown

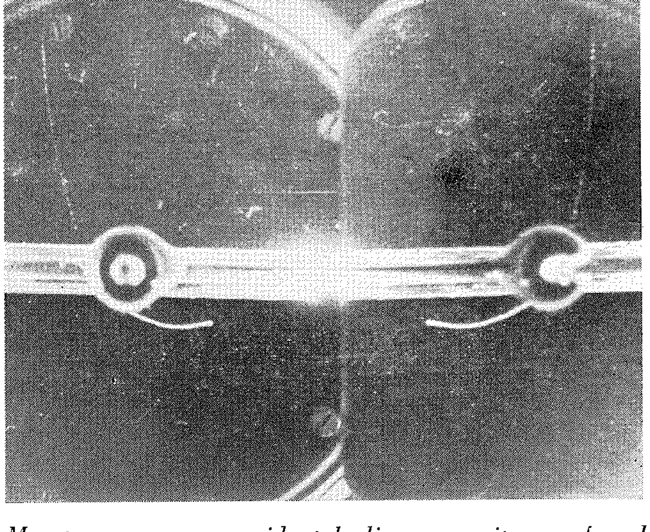


Positron above was produced by ordinary gamma rays from radioactive substances. Picture marks first time positron was found in other than the cosmic rays.

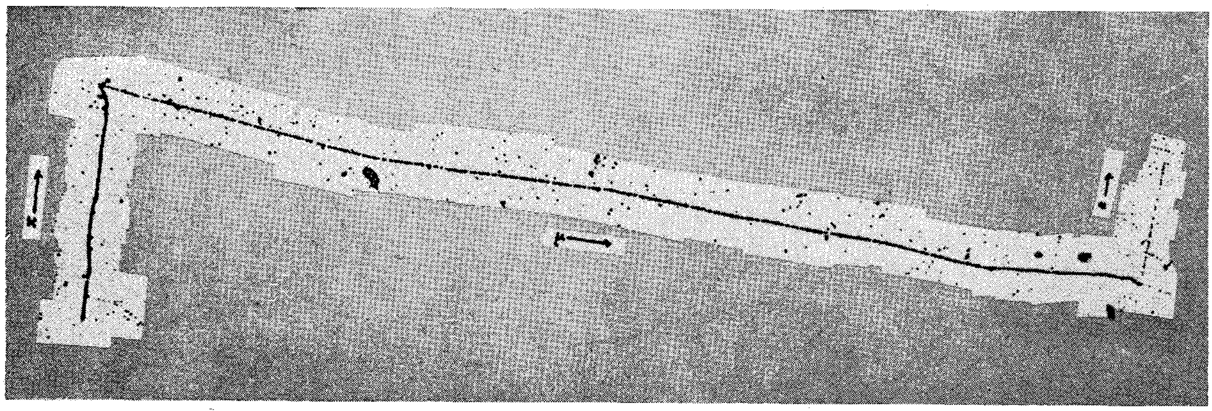
that in all probability the spontaneous disintegration of a mesotron results in the simultaneous production of an electron and two *neutrinos*. Neutrinos are the interesting elementary particles which had previously been invented in order to balance energy and momentum in the process in which an electron is produced when a radioactive nucleus decays. A similar situation exists in the case of the decay of a mesotron, except that here, because the mesotron disappears entirely, it is necessary to postulate the emission of *two* neutrinos in order to balance energy and momentum.

In free space, mesotrons spontaneously decay after about two millionths of a second. In the presence of matter, a mesotron of negative charge may terminate its existence in an even shorter time. It does this by entering an atomic nucleus or, in the language of the physicist, by undergoing nuclear capture.

The mesotrons observed in cosmic rays are produced



Mesotron was no accidental discovery; it was found after an exhaustive four-year effort to track down the countless clues to the existence of such a particle.



In Bristol, England, C. F. Powell is now analyzing tracks produced by mesotrons in emulsions of photographic plates. The track above shows how the decay of a pi mesotron (left) produces a mu mesotron (long horizontal line), which decays in turn to produce the electron whose track is shown at the right.

by the very high energy particles of the primary cosmic ray beam as it comes into the earth from outer space and plunges through the earth's atmosphere. In a manner somewhat analogous to the creation of positrons and electrons, the mesotrons are born out of the tremendous energies carried by the primary beam.

There are many interesting phenomena involved in the birth and death of mesotrons and in the violent nuclear processes which accompany these phenomena. Though it will not be possible to discuss them here I should like to mention in this connection two important advances which have been made in the last two years.

A new type of mesotron

One of these is the work under way in Bristol, England, by Powell and his co-workers, which has consisted of a detailed analysis of the tracks produced by mesotrons in the emulsions of photographic plates. These investigators have discovered a mesotron of a new type which is heavier than the ordinary mesotron. It is about 285 times as massive as an electron, whereas the ordinary mesotron is about 215 times as heavy. The heavy mesotron has a very short life; it lives only about one-one hundredth as long as the light mesotron, after which time it disintegrates and produces a light weight mesotron and another particle, which is probably a neutrino. The negatively charged heavy weight mesotron may also directly enter an atomic nucleus and give rise to a violent nuclear disruption.

Although both the newly discovered heavy mesotrons and the light mesotrons discovered in 1936 have some properties in common—both types of particles occur with positive and negative charges, both have short lives, and both are found in cosmic rays—nevertheless in some very fundamental respects they are entirely different types of elementary particles. The heavy mesotron interacts very strongly with atomic nuclei, but the light mesotron interacts only very weakly with atomic nuclei. Another difference lies in the respective values of that important property known as the spin or angular momentum; recent researches indicate that the heavy mesotron has an integral spin while the light mesotron has a half-integral spin.

In all probability it is the heavy mesotron and not the light mesotron which is to be identified with the particle first postulated on theoretical grounds by Yukawa in 1934. The theory of Yukawa, even in its present state, is very primitive. However, it still provides the best basic concept in terms of which to understand processes involving mesotrons, and after further development, the theory may provide an understanding in terms of mesotron exchange forces of that all-important problem as to the nature of the forces acting between the particles inside a nucleus. So far no satisfactory theory has been developed in terms of which to understand many of even the simplest phenomena involving the nucleus. To acquire a quantitative understanding of the interactions of elementary particles of matter and of fundamental nuclear processes is one of the great tasks of theoretical physics today.

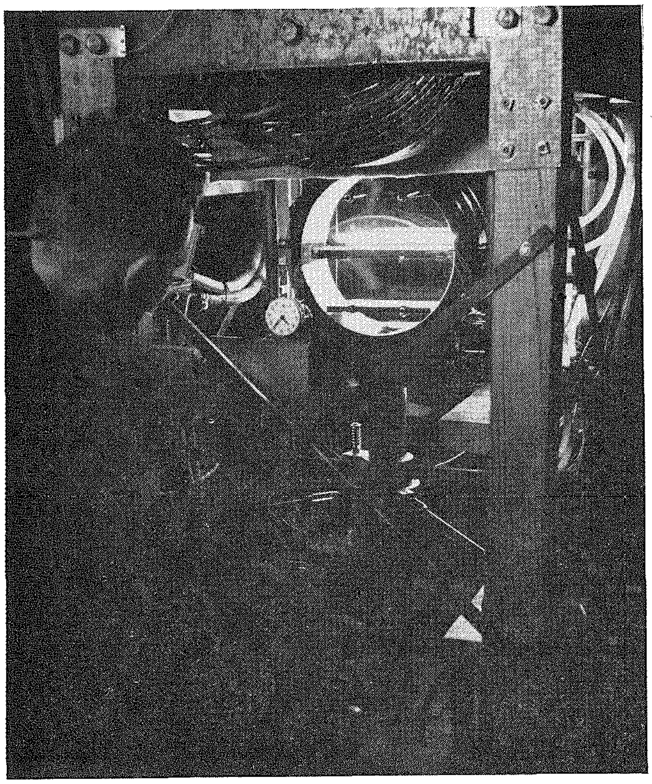
To complete our list of elementary particles we should perhaps include also the *photon.* This particle and the neutrino are, however, in a somewhat different category from the other types of particles. The photon is not a *material* particle in the sense that it cannot be identified with any particle which can exist at rest, and have associated with it a finite amount of ponderable material substance. Photons are to be identified only with radiation or radiant energy. The neutrino must also be placed in a special category, since it cannot have associated with it an appreciable amount of ponderable material substance—if any at all—and since it has never been directly observed.

In all, then, the physicist at the present time recognizes at least ten distinct elementary particles of matter. Whether this list is complete or not no one can say with certainty. The indications are that it is not, for evidence seems to be rapidly accumulating for the existence of at least one additional elementary particle. This particle is found in cosmic rays and appears to have a mass some one thousand times the mass of the electron. But what its properties are, and how it is related to the light and heavy mesotrons, and to the other elementary particles of matter, is a subject which must await the results of further observations.

The thought of probable further additions to the list of elementary particles of matter suggests a question which is quite apart from physics, and has to do simply with the naming of new particles. We have here, actually, an interesting example of the great difficulties that physicists sometimes have merely in assigning labels or names to the various concepts which their experiments or theories may bring forth. It is usually necessary to choose some sort of name for these concepts (whether they be elementary particles of matter or something else) before all the facts regarding them are known. In 1937 the term mesotron was suggested to designate the new particle of intermediate mass discovered in the cosmic rays in 1936. Since then this term has often been contracted to meson and has been so employed. Since the discovery of the new particle whose mass is greater than the mass of the original cosmic ray mesotron, the term mesotron or meson has been employed to designate both types of particles and the Greek letter prefixes *pi* and *mu* used to differentiate between them. Thus the term *pi* mesotron or *pi* meson designates the heavier particle and *mu* mesotron or *mu* meson designates the lighter particle. This nomenclature, in spite of the inconveniences resulting from the use of Greek letter prefixes, seemed satisfactory until continued experimentation began to show more and more clearly the important basic differences between the two types of particles.

It is beginning to be quite apparent now that the properties of these two types of particles are such that they will not naturally fall into the same classification. Thus the use of a common generic term such as mesotron or meson to designate both these types of particles may in the future prove to be inconvenient and illogical. Just what should be done with respect to nomenclature at this time is not clear, but it is a matter which should receive serious consideration, especially in view of the apparent entry of still another new elementry particle into the fold. Perhaps a committee of very wise souls should be assembled to make recommendation, and set a day for a great christening party to be attended by all the physicists in the world.

Another important advance that I want to mention is the recent success in producing mesotrons in the large cyclotron on the University of California campus at Berkeley. This represents the first time that it has been possible by artificial or laboratory means to imbue a single particle of matter with an energy sufficiently high to make possible the creation of mesotrons. This they have succeeded in doing in Berkeley with their beam of alpha-particles or helium nuclei which have been accelerated to an energy of 400 million electron volts. They observe the production of both the heavy and light mesotrons, and all indications are that the mesotrons they produce are identical with those previously observed among the particles produced by cosmic rays.



Robert B. Leighton, Research Fellow, looks into cloud chamber which first revealed that the mu mesotron decays into an electron and two neutrinos.

Now in the design stage are other particle-accelerating machines which will yield particle energies several times the 400 million electron volts so far achieved in the Berkeley cyclotron. When these machines are in operation, working at energies up to six or seven billion electron volts, we can expect to learn much more about mesotrons and the other elementary particles.

Moreover, we must expect that a continuation of research in cosmic rays will also extend our knowledge in this field, since in the cosmic rays, particles are available for study whose energies are even ten to a hundred thousand times greater than those to be expected from any of the accelerators being planned.

In this discussion I have classified physical phenomena according to the energy associated with them, into three categories: (1) low energy or extra-nuclear phenomena, (2) high energy or nuclear phenomena, and (3) extremely high energy or what we might call, for want of a better name, elementary particle phenomena. Knowledge of the first of these, low energy or extra-nuclear phenomena, has already profoundly affected the life of nearly every human being on earth. The Industrial Revolution, our mechanized civilization, the shrinking of the world through advances in communication and transportation have all come as a direct application of our knowledge of low energy or extra-nuclear phenomena. Indirectly it has been responsible for the political and economic organization of the whole world. Our present age might well be classified as an extra-nuclear age.

Since the explosion of the atomic bomb, and the achievement of the release of nuclear energy on a large scale, it seems rather clear that we are now entering a new period in which nuclear phenomena are destined to have an important part in shaping the world, politically if not economically, in the very near future.

It is only fifty years since our direct knowledge of the electron was not much more than a faint green glow in a glass tube—and now no one would deny that our knowledge of the properties of the electron has had an effect of profound importance in shaping our civilization. It is also only about fifty years since the world's knowledge of nuclear phenomena consisted of nothing more than the thoughts passing through the mind of Becquerel as he pondered a darkened arc on a photographic plate. At present our knowledge of all these fields is incomplete, but particularly is this true of nuclear phenomena, and most particularly true of high energy phenomena—elementary particle phenomena.

So far, the world's knowledge of the phenomena of high energies or the interactions between the elementary particles is represented by nothing more than a few printed pages in the scientific journals, by discussions among physicists, or perhaps by an occasional lecture. But we can look forward with anticipation and even excitement to the new discoveries which are surely to come as studies are carried forward of elementary particles and very high energy processes. New phenomena of great beauty, extreme complexity and novelty are certain to be revealed and finally understood.

Whether our knowledge of these new phenomena will then exert a great or a small influence on the world as a whole no one can say. I believe it would be most unwise, however, in the light of the history of scientific development, to expect this influence to be small.