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Structure of Physical Science

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On reading the title given to this symposium, "Fundamental units and concepts of science," my first intention was to make a rather general presentation of the basic problems that confront the physical scientist—the physicist, the astronomer, the chemist, the geologist. But I am not a specialist in generalities, and I fell into an obvious trap. If you ask a man who works on units about units, he will very likely tell you about units. I made a draft of a paper on this subject and sent it off to our major and distinguished commentator, Michael Polanyi, and I received the following reply: "My first impression of your contribution is that, by contrast with the biologists and sociologists, you are not worried at all about what you are doing in science." I took this comment to mean that Polanyi did not want to hear about units. And I am only too happy to agree with him, provided that he allows me to use my favorite motto. It is the moral from one of James Thurber's *Fables for Our Time,* and it goes, "It is better to know some of the questions than all of the answers."

Nonetheless, I regard it as something of a pity that I am not going to talk about units and standards. I have either the great fortune or the great misfortune always to be interested in what I am doing, and at this time in my life I am working on standards of time. I would like nothing better than to address a captive audience on the fine, basic scientific questions that might be answered by intercomparisons of various kinds of clocks. Similarly, it would be entertaining, to me at least, to discuss the significance of a quantity called "the velocity of light." Although, at the moment, there seem to be no measurements which show that "the velocity of light" is varying from year to year, I regard it as of some importance to try to understand the significance of the questions that such a variation would raise. The velocity of light is now known to only about 1 part in a million. There are at present groups of experimenters who are trying to improve this precision by some orders of magnitude. In fact, I believe that it will be possible to obtain, within the next decade, a precision of 1 part in 10^{12}, or 1 part in a British billion. But this kind of thing is not appropriate to this occasion, so let me leave it.

After some preliminary discussion, I want to arrive at a simplified description of what I consider to be the basic problems that confront the physical scientist, qua scientist. I am carefully avoiding all the problems that confront him as a technologist, as a citizen, as a humanitarian, as a philosopher, or even as a teacher of the young, although nothing would give me more pleasure than to talk about what some of us are doing to try to make teaching physics in the secondary schools a bit easier and a bit more effective.

Particles and Forces

As for these basic principles, it will be helpful first to establish a pattern in which the subject of physics and its closely associated sister sciences fall. This is especially so because one can describe such a tidy package. We consider (i) the particles that are involved; (ii) the laws of force that these particles obey; (iii) the laws of motion that result from the interaction of the particles with these forces; (iv) the mathematical calculations that permit (v) the experimental observations that can be compared with the theory in order to see whether the particles and the laws of force and laws of motion are appropriate to a description of nature. In order to clarify this framework, let me apply it to some well-known cases.

One of the oldest, simplest, and most beautiful examples exists in that branch of astronomy which deals with our solar system. This particular instance may be regarded as a prototype of most of the problems of physical science. The sun and its planets and the satellites of the planets are the particles. Newton's law of gravitation is the law of force. Every particle in the universe attracts every other particle with a force which is proportional to the inertial masses of the particles and which varies inversely with the square of the distance between them. Newton's law of motion predicts where the particles will go, given a knowledge of where they were at some earlier time. And, with modern computing machinery, it is now possible to compare observations on planetary and lunar motions with theory. In fact, lunar motions can be predicted to about 1 part in 10^9, which until recently was considered admirable.

At the risk of laboring what is well known, let me point out that the explanation of the motion of the planets by the laws of gravitation and the laws of motion makes a superb example of that round-robin process which is characteristic of science. In first approximation, the particles involved (the sun and the planets) *were* known, and the gravitational law of force and the Newtonian law of motion yielded predictions that were correct within the limits of observation. Subsequently, more refined measurements, of course, led to the discovery of unknown planets. In addition, Einstein's modification of Newton's law of motion has been found to be necessary for describing a slight perturbation in the orbit of Mercury. So far, the law of gravitation appears to be holding up well, although I am willing to bet that the next decade will see considerable discussion of the law of gravity, not the least provocative of which will be the ques-

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tion of the gravitational effects of antimatter.

Take another example, the structure of atoms and molecules. The particles are the atomic nuclei and their circumambient electrons. The forces involved are all manifestations of Coulomb's law. Like charges repel, and unlike charges attract each other with a force that varies inversely as the square of the distances between them. (One may remark here that, in *all* of atomic and molecular physics, in *all* solids, liquids, and gases, and in *all* things that involve our relationship with our environment, the *only* force law, besides gravity, is some manifestation of this simple law. Frictional forces, wind forces, chemical bonds, viscosity, magnetism, the forces that make the wheels of industry go round—all these are nothing but Coulomb's law, as simple as the force at work when you pick up a piece of paper with a fountain pen that has been rubbed on your sleeve.) Of course, the laws of motion are not those of Newton but are the wave mechanics of Schrödinger, Born, Dirac, and Heisenberg. Unfortunately, even the best computing machines are still having trouble with all but the most simple systems. The mathematical problems of the hydrogen atom, with only two particles, can be solved with great precision. So far, the more complicated problems of atoms heavier than hydrogen and of molecules of liquids and of solids yield to degrees of precision that suffice only to test the adequacy of the mathematical methods. Laws of nature that apply to all matter and to all radiation rarely emerge from a detailed consideration of systems importantly involving more than two particles at a time. Of necessity, the Pauli principle is an exception, and so, too, are those cases in which there is enough chaos to make things simple again.

The next example is that of the atomic nucleus. We believe that we know what particles are involved—we talk of protons and neutrons in the nucleus. We admit that, with some provocation, other particles can be emitted by a nucleus—electrons and antielectrons; neutrinos and antineutrinos; mesons, plus and minus; pions, plus, minus, and neutral; heavy mesons; hyperons; and so on. But there is evidence that, most of the time, protons and neutrons make a good first approximation to the particles.

Basic Principles

Let us look first at the laws of motion. The quantum mechanics, so beautifully formulated for atomic problems, is probably appropriate for considerations of the motions inside the nuclear core. To be sure, extremely relativistic forms are required because the energies of the particles are large. One cannot regard the velocity of light as arbitrarily large. But the logical structure of the wave mechanics has made such profound philosophic changes in scientific thinking that we hesitate to give it up. Besides this, some of the features of the quantum mechanics which make it so different from Newtonian mechanics have been shown to hold for atomic nuclei.

We know very little about the details of the essentially nuclear forces. Even though we have much quantitative knowledge about the interactions in "two-body" problems like that of the deuteron and the scattering of one nuclear particle by another, we are in trouble with the many-body problem. Nuclear forces are so strong that nuclear material has a density of 10^{14}. The individual nuclear particles are so close to each other that we not only have mathematical difficulties, but we also have no assurance that the proximity of other particles leaves the interaction between pairs the same as it would be out in space. In summary, the short-range forces between particles (what we call nuclear forces) remain a challenging unknown.

However, there are other ways of looking at things so that they are not such a tidy package. So far, the idea of physics, and the ideas that are basic to the formulations of chemistry and the related sciences, depend essentially on the notion of force between particle pairs—the sun and the earth, the nucleus and the electron. For more complicated problems, we always assume that a third body may affect the positions of two others, but we have not yet made the bold assumption that the presence of a third body affects the type and magnitude of the forces between the first two. Let me state the general question this way: Are there physical effects of a new sort that arise simply from the existence of large aggregates of particles? Certainly this notion is elementary to the sociologists. Does matter in a high state of aggregation—as in atomic nuclei, as in the interiors of dense stars, as in solids or liquids even—behave differently from matter in the tenuous states? Certainly people do.

Yet another kind of problem faces us: the nature of a particle at very close hand—any particle, the whole zoo of fundamental particles that have come to occupy the attention of so many physicists in the last few years. There are two ways of stating this problem. One is to say that for forces that vary rapidly with the distance away from a point, the energies increase indefinitely as the distances become smaller. In the case of Coulomb force, we have, to be sure, a *gentle* logarithmic approach to infinite energy, but it is nonetheless troublesome. Another way to say it is that one uses mathematical point-functions in the problems of atomic physics and that the wave nature of everything gives less and less meaning to point positions. During the last 10 years there has been a continued precision approach to this problem, carried out by Lamb, Rabi, Kusch, Bethe, Weisskopf, Schwinger, and many others. But more spectacularly, there has been the approach of superhigh-energy physics, and when the smoke of battle clears away and the properties of the *new* particles are as well known as those of the old ones, we may have a better picture of a single particle.

The last problem I want to talk about is one that has baffled all of us since early childhood. What is the nature of matter and of radiation at points very remote from us, either in space or in time? What happens to light that we shine up into the sky? Where do those neutrinos go, which are manufactured in such profusion by all of the stars? Such questions give me the same visceral feelings that I experience when I contemplate infinity. For some reason that I do not understand, projections into the indefinite past always seem to be more emotionally charged than projections into the future.

Conclusion

Probably not more than 5 percent of professional physical scientists are working on direct attempts to formulate laws with such broad general applicability. Rather, they are finding out how to apply laws to special problems—molecules, simple and complex; solids, and liquids. In a similar way, nuclear physicists are spending most of their time on the properties of nuclei of mass greater than 2. I am sure that all of us—I know I do—work on such complicated problems.

In order to clarify, in case there is any doubt, I may cite some examples of the general and the specific. Snell's law—the law of refraction—and Ohm's law are properties of specific kinds of materials, whereas Coulomb's law and Newton's laws are properties of all matter.

We have found that frequently this important and not very subtle difference is lost in most of elementary physics teaching, and since I have never heard much discussion of this idea by the biologists or sociologists, I wonder whether they have their own way of saying these things. There certainly are statements of general laws.

I regard the doctrine of noninheritance of acquired characteristics as such a law in biology.

In sociology, the much-abused law of Malthus is also such a law. It is the trivially obvious one that we live on a finite sphere, and it voices the heartening optimism that man's technical skill to live will outrun man's technical skill to kill himself. In 1956 we seem to be in the less pleasant phase, but that phase must some day pass and Malthus will be right.