Chapter I

THE DOWNFALL OF CLASSICAL PHYSICS

The Structure of the Atom. Between 1905 and 1908 Einstein and Minkowski introduced fundamental changes in our ideas of time and space. In 1911 Rutherford introduced the greatest change in our idea of matter since the time of Democritus. The reception of these two changes was curiously different. The new ideas of space and time were regarded on all sides as revolutionary; they were received with the greatest enthusiasm by some and the keenest opposition by others. The new idea of matter underwent the ordinary experience of scientific discovery; it gradually proved its worth, and when the evidence became overwhelmingly convincing it quietly supplanted previous theories. No great shock was felt. And yet when I hear to-day protests against the Bolshevism of modern science and regrets for the old-established order, I am inclined to think that Rutherford, not Einstein, is the real villain of the piece. When we compare the universe as it is now supposed to be with the universe as we had ordinarily preconceived it, the most arresting change is not the rearrangement of space and time by Einstein but the dissolution of all that we regard as most solid into tiny specks floating in void. That gives an abrupt jar to those who think that things are more or less what they seem. The revelation by modern physics of the void within the atom is more disturbing than the revelation by astronomy of the immense void of interstellar space.

The atom is as porous as the solar system. If we eliminated all the unfilled space in a man's body and collected his protons and electrons into one mass, the man would be reduced to a speck just visible with a magnifying glass.

This porosity of matter was not foreshadowed in the atomic theory. Certainly it was known that in a gas like air the atoms are far separated, leaving a great deal of empty space; but it was only to be expected that material with the characteristics of air should have relatively little substance in it, and "airy nothing" is a common phrase for the insubstantial. In solids the atoms are packed tightly in contact, so that the old atomic theory agreed with our preconceptions in regarding solid bodies as mainly substantial without much interstice.

The electrical theory of matter which arose towards the end of the nineteenth century did not at first alter this view. It was known that the negative electricity was concentrated into unit charges of very small bulk; but the other constituent of matter, the positive electricity, was pictured as a sphere of jelly of the same dimensions as the atom and having the tiny negative charges embedded in it. Thus the space inside a solid was still for the most part well filled.

But in 1911 Rutherford showed that the positive electricity was also concentrated into tiny specks. His scattering experiments proved that the atom was able to exert large electrical forces which would be impossible unless the positive charge acted as a highly concentrated source of attraction; it must be contained in a nucleus minute in comparison with the dimensions of the atom. Thus for the first time the main volume of the atom was entirely evacuated, and a "solar system" type of atom was substituted for a substantial "billiard-ball". Two years later Niels Bohr developed his famous theory on the basis of the Rutherford atom, and since then rapid progress has been made. Whatever further changes of view are in prospect, a reversion to the old substantial atoms is unthinkable.

The accepted conclusion at the present day is that all varieties of matter are ultimately composed of two elementary constituents—protons and electrons. Electrically these are the exact opposites of one another, the proton being a charge of positive electricity and the electron a charge of negative electricity. But in other respects their properties are very different. The proton has 1840 times the mass of the electron, so that nearly all the mass of matter is due to its constituent protons. The proton is not found unadulterated except in hydrogen, which seems to be the most primitive form of matter, its atom consisting of one proton and one electron. In other atoms a number of protons and a lesser number of electrons are cemented together to form a nucleus; the electrons required to make up the balance are scattered like remote satellites of the nucleus, and can even escape from the atom and wander freely through the material. The diameter of an electron is about 1/50,000 of the diameter of an atom; that of the nucleus is not very much larger; an isolated proton is supposed to be much smaller still.

Thirty years ago there was much debate over the question of aether-drag—whether the earth moving round the sun drags the aether with it. At that time the solidity of the atom was unquestioned, and it was difficult to believe that matter could push its way through the aether without disturbing it. It was surprising and perplexing to find as the result of experiments that no convection of the aether occurred. But we now realise that the aether can slip through the atoms as easily as through the solar system, and our expectation is all the other way.

We shall return to the "solar system" atom in later chapters. For the present the two things which concern us are (1) its extreme emptiness, and (2) the fact that it is made up of electrical charges.

Rutherford's nuclear theory of the atom is not usually counted as one of the scientific revolutions of the present century. It was a far-reaching discovery, but a discovery falling within the classical scheme of physics. The nature and significance of the discovery could be stated in plain terms, i.e. in terms of conceptions already current in science. The epithet "revolutionary" is usually reserved for two great modern developments—the Relativity Theory and the Quantum Theory. These are not merely new discoveries as to the content of the world; they involve changes in our mode of thought about the world. They cannot be stated immediately in plain terms because we have first to grasp new conceptions undreamt of in the classical scheme of physics.

I am not sure that the phrase "classical physics" has ever been closely defined. But the general idea is that the scheme of natural law developed by Newton in the *Principia* provided a pattern which all subsequent developments might be expected to follow. Within the four corners of the scheme great changes of outlook were possible; the wave-theory of light supplanted the corpuscular theory; heat was changed from substance (caloric) to energy of motion; electricity from continuous fluid to nuclei of strain in the aether. But this was all allowed for in the elasticity of the original scheme. Waves, kinetic energy, and strain already had their place in the scheme; and the application of the same conceptions to account for a wider range of phenomena was a tribute to the comprehensiveness of Newton's original outlook.

We have now to see how the classical scheme broke down.

The FitzGerald Contraction. We can best start from the following fact. Suppose that you have a rod moving at very high speed. Let it first be pointing transverse to its line of motion. Now turn it through a right angle so that it is along the line of motion. The rod contracts. It is shorter when it is along the line of motion than when it is across the line of motion.

This contraction, known as the FitzGerald contraction, is exceedingly small in all ordinary circumstances. It does not depend at all on the material of the rod but only on the speed. For example, if the speed is 19 miles a second—the speed of the earth round the sun—the contraction of length is 1 part in 200,000,000, or $2\frac{1}{2}$ inches in the diameter of the earth.

This is demonstrated by a number of experiments of different kinds of which the earliest and best known is the Michelson-Morley experiment first performed in 1887, repeated more accurately by Morley and Miller in 1905, and again by several observers within the last year or two. I am not going to describe these experiments except to mention that the convenient way of giving your rod a large velocity is to carry it on the earth which moves at high speed round the sun. Nor shall I discuss here how complete is the proof afforded by these experiments. It is much more important that you should realise that the contraction is just what would be expected from our current knowledge of a material rod.

You are surprised that the dimensions of a moving

Cambridge University Press
978-1-107-66385-5 - The Nature of the Physical World: Gifford Lectures 1927
A. S. Eddington
Excerpt
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rod can be altered merely by pointing it different ways. You expect them to remain unchanged. But which rod are you thinking of? (You remember my two tables.) If you are thinking of continuous substance, extending in space because it is the nature of substance to occupy space, then there seems to be no valid cause for a change of dimensions. But the scientific rod is a swarm of electrical particles rushing about and widely separated from one another. The marvel is that such a swarm should tend to preserve any definite extension. The particles, however, keep a certain average spacing so that the whole volume remains practically steady; they exert electrical forces on one another, and the volume which they fill corresponds to a balance between the forces drawing them together and the diverse motions tending to spread them apart. When the rod is set in motion these electrical forces change. Electricity in motion constitutes an electric current. But electric currents give rise to forces of a different type from those due to electricity at rest, viz. magnetic forces. Moreover these forces arising from the motion of electric charges will naturally be of different intensity in the directions along and across the line of motion.

By setting in motion the rod with all the little electric charges contained in it we introduce new magnetic forces between the particles. Clearly the original balance is upset, and the average spacing between the particles must alter until a new balance is found. And so the extension of the swarm of particles—the length of the rod—alters.

There is really nothing mysterious about the Fitz-Gerald contraction. It would be an unnatural property of a rod pictured in the old way as continuous substance occupying space in virtue of its substantiality; but it is an entirely natural property of a swarm of particles held in delicate balance by electromagnetic forces, and occupying space by buffeting away anything that tries to enter. Or you may look at it this way: your expectation that the rod will keep its original length presupposes, of course, that it receives fair treatment and is not subjected to any new stresses. But a rod in motion is subjected to a new magnetic stress, arising not from unfair outside tampering but as a necessary consequence of its own electrical constitution; and under this stress the contraction occurs. Perhaps you will think that if the rod were rigid enough it might be able to resist the compressing force. That is not so; the FitzGerald contraction is the same for a rod of steel and for a rod of india-rubber; the rigidity and the compressing stress are bound up with the constitution in such a way that if one is large so also is the other. It is necessary to rid our minds of the idea that this failure to keep a constant length is an imperfection of the rod; it is only imperfect as compared with an imaginary "something" which has not this electrical constitution—and therefore is not material at all. The FitzGerald contraction is not an imperfection but a fixed and characteristic property of matter, like inertia.

We have here drawn a qualitative inference from the electrical structure of matter; we must leave it to the mathematician to calculate the quantitative effect. The problem was worked out by Lorentz and Larmor about 1900. They calculated the change in the average spacing of the particles required to restore the balance after it had been upset by the new forces due to the change of motion of the charges. This calculation was found to give precisely the FitzGerald contraction, i.e. the amount already inferred from the experiments above mentioned.

Thus we have two legs to stand on. Some will prefer to trust the results because they seem to be well established by experiment; others will be more easily persuaded by the knowledge that the FitzGerald contraction is a necessary consequence of the scheme of electromagnetic laws universally accepted since the time of Maxwell. Both experiments and theories sometimes go wrong; so it is just as well to have both alternatives.

Consequences of the Contraction. This result alone, although it may not quite lead you to the theory of relativity, ought to make you uneasy about classical physics. The physicist when he wishes to measure a length—and he cannot get far in any experiment without measuring a length—takes a scale and turns it in the direction needed. It never occurred to him that in spite of all precautions the scale would change length when he did this; but unless the earth happens to be at rest a change must occur. The constancy of a measuring scale is the rock on which the whole structure of physics has been reared; and that rock has crumbled away. You may think that this assumption cannot have betrayed the physicist very badly; the changes of length cannot be serious or they would have been noticed. Wait and see.

Let us look at some of the consequences of the FitzGerald contraction. First take what may seem to be a rather fantastic case. Imagine you are on a planet moving very fast indeed, say 161,000 miles a second. For this speed the contraction is one-half. Any solid contracts to half its original length when turned from across to along the line of motion. A railway journey between two towns which was 100 miles at noon is shortened to 50 miles at 6 p.m. when the planet has turned through a right angle. The inhabitants copy Alice in Wonderland; they pull out and shut up like a telescope.

I do not know of a planet moving at 161,000 miles a second, but I could point to a spiral nebula far away in space which is moving at 1000 miles a second. This may well contain a planet and (speaking unprofessionally) perhaps I shall not be taking too much licence if I place intelligent beings on it. At 1000 miles a second the contraction is not large enough to be appreciable in ordinary affairs; but it is quite large enough to be appreciable in measurements of scientific or even of engineering accuracy. One of the most fundamental procedures in physics is to measure lengths with a scale moved about in any way. Imagine the consternation of the physicists on this planet when they learn that they have made a mistake in supposing that their scale is a constant measure of length. What a business to go back over all the experiments ever performed, apply the corrections for orientation of the scale at the time, and then consider *de novo* the inferences and system of physical laws to be deduced from the amended data! How thankful our own physicists ought to be that they are not in this runaway nebula but on a decently slow-moving planet like the earth!

But stay a moment. Is it so certain that we are on a slow-moving planet? I can imagine the astronomers in that nebula observing far away in space an insignificant star attended by an insignificant planet called Earth. They observe too that it is moving with the huge velocity of 1000 miles a second; because naturally if we see them receding from us at 1000 miles a second they will see us receding from them at 1000 miles a second. "A thousand miles a second!" exclaim the nebular physicists, "How unfortunate for the poor physicists on the Earth! The FitzGerald contraction will be quite appreciable, and all their measures with scales will be seriously wrong. What a weird system of laws of Nature they will have deduced, if they have overlooked this correction!"

There is no means of deciding which is right—to which of us the observed relative velocity of 1000 miles a second *really* belongs. Astronomically the galaxy of which the earth is a member does not seem to be more important, more central, than the nebula. The presumption that it is we who are the more nearly at rest has no serious foundation; it is mere self-flattery.

"But", you will say, "surely if these appreciable changes of length occurred on the earth, we should detect them by our measurements." That brings me to the interesting point. We could not detect them by any measurement; they may occur and yet pass quite unnoticed. Let me try to show how this happens.

This room, we will say, is travelling at 161,000 miles a second vertically upwards. That is my statement, and it is up to you to prove it wrong. I turn my arm from horizontal to vertical and it contracts to half its original length. You don't believe me? Then bring a yard-measure and measure it. First, horizontally, the result is 30 inches; now vertically, the result is 30 half-inches. You must allow for the fact that an inch-division of the scale contracts to half an inch when the yard-measure is turned vertically.

"But we can see that your arm does not become shorter; can we not trust our own eyes?"

Certainly not, unless you remember that when you got up this morning your retina contracted to half its original width in the vertical direction; consequently it