# The Progress of Physics From 1848 to 1948

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I HAVE BEEN ASKED TO MAKE a contribution to this Centennial Celebration of the AAAS by some kind of a review of the progress of physics since 1848. In attempting to do so, it is first necessary to provide a picture of the state of science in the United States in the 1840's. I shall try to do this by first quoting a few lines from a recent Atlantic Monthly Press book entitled *New world picture,* by George W. Gray, who, in the following words reflects the state of astronomy in this country at that time. That this picture holds for all the sciences is probable in view of the fact that astronomy is not only the oldest of the sciences, but at all times has been the world over the most generally popular of them all. He says:

> In 1832 the English astronomer Airy, in making a report to the British Association on the state of astronomical science throughout the world, remarked that he was unable to say anything about American astronomy because, so far as he knew, no public observatory existed in the United States. It was in the 1840's that the Cincinnati Observatory, the Naval Observatory in Washington, and the Harvard College Observatory in Cambridge, Massachusetts, were founded—the three pioneer institutions in a development that has continued with increasing acceleration ever since. To-day there are more first-class public observatories in the United States than in all the rest of the world, and their equipment is so superior as to make astronomical observation in the twentieth century almost exclusively an American science. For the interpretation of American observations, though, European astronomers and physicists have contributed more than their per capita share—and science is still the great International.

But what was the state of *world* science, as distinct from that of American science, a hundred years ago? Here is my answer to that question: The great foundation, not only of physics but of all the natural sciences and their applications, had been laid in the development following the publication in 1687 of the *Principia* of Galilean-Newtonian mechanics, which by 1800 had made such an impression upon Lagrange, greatest of French mathematical physicists, that he called Newton not only (I quote) "the greatest genius that had ever existed, but also the most fortunate, for there is but one universe and it can happen to but one man in the world's history to be the interpreter of its laws." True, Newton was too great a man to be guilty of such extreme dogmatism (defined as assertiveness without knowledge), for he not only described himself as "like a boy, playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, while the great ocean of truth lay all undiscovered before me." He also wrote in his *Opticks*: "The main business of Natural Philosophy is to argue from phenomena without feigning (asserting) hypotheses, and to deduce causes from effects till we come to the very first cause, *which is certainly not mechanical.*"

"To Newton," says the historian of science, Sir William Dampier, "God is immanent in Nature." Lagrange can be excused for being so terrible dogmatist at his date, since he never had a chance to attend a modern symposium on cosmic rays or quantum mechanics. In that sentence I have touched upon what is probably the greatest contribution of physics to human life in our century (1848–1948), namely, the lesson of not extending our working hypotheses with too much cocksureness beyond the range of their experimental verification, for the universe does not lie within the horizon of any mortal, be he scientist or churchman.

Let us return now to other elements of our knowledge of physics in 1848. The wave theory of light had been developed about 1818–20 with matchless skill and completeness by one of France's greatest geniuses, Augustin Fresnel. Again, the foundations for the understanding of electrostatic phenomena had been amazingly well laid by Benjamin Franklin, the most penetrating scientific mind of his time—for what he, altogether without training, contributed in the brief 6 years (1747–53) in which he worked in this field entitles him to rank foremost among American scientists. Volta in Italy (1800) had added notably to the foundations laid by Franklin; Oersted, the Dane (1819), had made the great discovery of electromagnetism; Ampere, the Frenchman, in the 1920's had developed that field with great skill and insight; while England's unsurpassed experimentalist, Faraday, had in 1931 discovered electromagnetic induction and in 1934 had laid the secure foundation for the whole field of electrolysis.

But of the subjects treated in the conventional subdivisions of physics the relations of heat and work and the properties of gases had lagged behind and were but little understood, though plenty of speculating had been done about them. This was the situation in the whole field of heat effects in spite of the success of the Scotch inventor, James Watt, in producing the steam engine and getting it into practical operation between 1765 and 1782. The existence and rapidly growing use of this engine was responsible for the appearance, in 1824, of one of the greatest scientific advances ever made in physics, namely, the discovery through the use of a new type of reasoning, called reversible Carnot cycles, of the second law of thermodynamics. Its author, at the age of 28, published in that year a small book entitled *Reflections on the motive power of heat and upon the machines to develop this power.* In this, Captain Sadi Carnot, "who had studied mathematics, chemistry, physics, technology, and even political economy, who was an enthusiast in music and other fine arts and practiced in all sorts of athletic sports, including swimming and fencing, reveals himself also as an original and profound thinker. This book contains but a fragment of his scientific discoveries, but it is sufficient to put him in the very foremost rank though its full value was not recognized until pointed out by Lord Kelvin in 1848 and 1849." This appraisal of Carnot, quoted from the last edition of the *Encyclopaedia Britannica,* introduces us to one of the three stupendous advances in physics (in addition to the birth of the AAAS!) which ushered in the century with which we are concerned in this celebration.

The first of these three advances was the formulation, primarily through the experimental work of Joule which appeared first in 1847, of "The Equivalence of Heat and Work," commonly called the first law of thermodynamics, which was expanded by the reasoning of Kelvin, Mayer, and Helmholtz into the statement of the Principle of the Conservation of Energy—the most far-reaching generalization in the whole range of physical science and one which should always be stated as a working hypothesis, an hypothesis which we can never fully *prove* correct because we shall never be able to test all possible cases.

If the principle of the equivalence of heat and work is assumed, then, as Kelvin showed in 1848, it is possible to *prove* the correctness of the conclusion at which Carnot arrived, namely, the principle that all reversible engines working between the same two temperatures must have the same thermodynamic efficiency. This second law of thermodynamics is sometimes called "The Principle of Entropy." The introduction into our modern languages of the words "energy" and "entropy" as sharply defined physical concepts was due primarily to the work of Joule, Kelvin, Mayer, and Helmholtz at the very beginning of the century 1848–1948.

The third of the great advances referred to above as coming in with our century was the appearance of the first definite quantitative evidence through the analysis of Joule in England and Clausius in Germany for the correctness of the Kinetic Theory of Gases. This work of Joule and Clausius on the kinetic theory, coming in at the very opening of our century, began to give physicists confidence in the validity and usefulness of the atomic and kinetic postulates underlying the kinetic theory. That confidence was increased by the appearance about 1865 of a notable paper by James Clerk Maxwell in which he showed that the kinetic theory required that the viscosity of a gas within wide limits should be independent of its density or pressure. At first sight this looked like an impossible result, quite contrary to common sense, but Maxwell devised an experiment which proved that the requirements of his theory were met experimentally and quantitatively, too. This introduces James Clerk Maxwell to the century on review today. *He was its greatest ornament*—probably the greatest analytical mind since Newton. He and his electromagnetic theory dominated all the rest of the 19th Century. He first advanced his electromagnetic theory in a paper which appeared in 1867, but elaborated it in his book, *Electricity and magnetism,* published in 1873. In this he predicted what we now call radio waves and proved that light was only short wave-length waves of this sort.

In 1888 Heinrich Hertz first produced such radio waves in his laboratory at Karlsruhe and found that their speed of transmission was the same as that of light, as it had to be if Maxwell's theory was correct. Helmholtz, at the University of Berlin, began at once a course of lectures on the applications of the electromagnetic theory to optics. Drude, one of Helmholtz' pupils, following the outline of Helmholtz' lectures as filtered through his own mind, wrote a book entitled *Physik des Aethers* (1897), which Riborg Mann and I translated into English. Maxwell's theory was spread through agencies of this sort and became the chief subject of study in the world's physical and electrical engineering laboratories, so that it is not too much to say that Maxwell's book has created the present age of electricity in much the same way in which Newton's *Principia* created, a hundred years earlier, the mechanical age in which we are still living. Probably no books have ever exerted so large an influence on the life of man on earth as have these two.

Turn now from the fields of thermodynamics and electrodynamics, with their infinitude of applications to the life of man, to the field of relativity, which has had few, if any, immediate applications to the everyday life of mankind. It, too, is a product of the century under review. It was in 1888, when Hertz was testing out Maxwell's theory of electromagnetic waves, that Michelson and Morley were making in Cleveland their famous ether drift experiment, in which they found no trace of a relative motion of the earth through the ether, or through space, if one prefers that form of statement. The generalization of the negative results of that experiment is the origin of the relativity theory. One of the most important consequences of the experiment has been to convince us all that *we did not know as much about the universe as we thought we did.* We have tried to reconstruct our universe so that there will not be any contradictions left in it, but we have woefully failed in the attempt, and possibly that knowledge *about our limitations* is just as useful for our intelligent and satisfying living as the practical knowledge we obtained from our studies in thermodynamics and electrodynamics. I shall return to this question after considering some other discoveries of our century that have been made since 1895.

The first four of these are (1) the discovery of X-rays by Roentgen in December 1895, (2) the discovery of radioactivity by Becquerel in Paris in 1896, (3) the demonstration to the satisfaction of physicists generally, by J. J. Thomson in England in 1897, of the concept of the electron as a fundamental constituent of all the atoms in the universe, and (4) the discovery of "quanta" by Planck in Berlin in 1900.

Of these four discoveries, the electron has been the most useful to mankind, for there is scarcely an industry that does not use it, and many new industries have been created by it. Radioactivity has been the most spectacular of the four, the most startling to human thought, and the most stirring to human imagination, for it destroyed the idea of the immutability of the elements and showed that the dreams of the alchemists might yet come true.

Planck's discovery of quanta had the most profound influence of any of the other three discoveries upon the fundamentals of physics. It was not revolutionary in undoing the past. The old laws still held *in the field in which they had been experimentally tested.* The reason the discovery had not been made earlier is that man was here entering an almost completely unexplored domain of the very existence of which he had thus far scarcely dreamed, namely, the domain of subatomic or microscopic, as distinguished from ordinary or macroscopic, energy or momentum exchanges. Practically the whole of our lives is still spent in the macroscopic world of ordinary, large-scale phenomena, in which energy exchanges are continuous processes described by differential equations and governed by the established laws of Galilean-Newtonian mechanics. In the discovery of quanta, man entered for the first time a new atomic, or microscopic, world in which *continuous* changes, with their laws, no longer rule, but where, instead, all energy exchanges represent sudden, discrete energy jumps that we call "quanta," defined by the product $h\nu$, where $h$ is a universal constant called "Planck's h" and $\nu$ is the frequency of the vibration involved. Planck was led to his announcement of the theory of quanta through a whole series of results obtained mainly in Germany, first by Vienna's greatest physicist, Boltzmann, in 1884 on the law of so-called black-body or "cavity radiation" (the Stefan-Boltzmann law); second, by the German physicist, Wien, on the Wien displacement law (see *Wied. Ann.*, 1896, **58**, 662). Both these laws follow necessarily from thermodynamic reasoning applied to cavity radiation. Third came Lummer and Pringsheim's experimental studies at the Berlin Reichsanstalt (1897–99) on the actual distribution of radiant energy between the different wave lengths in black-body radiation, and fourth, the combination of these results, showing that the "principle of equipartition" could not apply to black-body radiation and that *quanta* were the only way out of the difficulty.

The next three important discoveries of our century were made by Rutherford in 1911, by Moseley in 1914, and by Bohr in 1913. All of these relate to the microscopic, not the macroscopic, world and therefore find their utility only in increasing man's understanding of the way the world in which he lives does its day-by-day business. The discovery, made in 1914 by Moseley, a brilliant young Englishman who lost his life at Gallipoli in World War I, consisted in proving that there neither are nor can be more than 92 different stable elements, all of which have from 1 up to 92 positive unit-charges on their minute central nucleus and which therefore can hold from 1 up to 92 satellite negative electrons circling about that nucleus. Moseley therefore simplified our whole understanding of atomic constitution by introducing as the unique and distinguishing characteristic of a given atom its *atomic number* in the complete sequence extending from 1 up to 92. At the age of 27 he had accomplished as notable a piece of research in physics as had appeared in 50 years.

The Rutherford discovery of 1911 was the discovery of the nuclear atom itself, utilized after its discovery by Rutherford in Moseley's researches. In 1903 Rutherford had already done more than any one physicist to clear up and reduce to order the complicated mass of radioactive data and thus reduce radioactivity to an orderly and quite-well-understood science. He did a similar job for the structure of the atom in 1911, demonstrating by straightforward analysis what the structure of the atom had to be to account for the way it acted upon alpha particles shot through it. He did a third great job in 1919, when, using alpha particles as his bullets, he produced the first artificial disintegration of atoms by knocking protons out of nitrogen, aluminum, and phosphorus. He was an indefatigable worker himself, and he was a great director of three laboratories—one at McGill University in Canada; one at Manchester, England; and one at Cambridge, England.

Rutherford made no use of quanta in arriving at his picture of the Rutherford nuclear atom, which was simply a small central nucleus carrying a number of unit positive charges determined by, and equal to, the *atomic number* of the atom.

Bohr, on the other hand, devised an atom which could emit or absorb radiations in all its atomic shells, and each such emission or absorption represented a quantum jump from one of a whole series of quantized orbits to another. In other words, it was an atom designed to handle the emission of line spectra; it was a *spectroscopic* atom. When it was devised, spectroscopy was a veritable dark continent in physics. With the aid of the Bohr atom the dark continent in physics has become the best-explored, the best-understood, and the most civilized portion of the world of physics. It has been an exciting game of exploration to which a whole group of the ablest young men in physics have contributed—men like Chadwick, discoverer of the neutron; Pauli, of "Pauli's exclusion rule" fame[1]; and Bowen, who brilliantly solved the century-old riddle of the nebulium lines and demonstrated that these mysterious lines are all merely "forbidden lines," corresponding to electronic jumps in common atoms like carbon, nitrogen, oxygen, which jumps cannot take place while the atoms are participating in collisions frequently occurring between them and their neighbors, but can take place in the essential absence of collisions such as is to be expected in outer space or in tenuous nebulae. Mysterious nebulium thus became ordinary carbon, nitrogen, and oxygen.

Because of space limitations I have not treated Carl Anderson's discovery of the positron, Anderson and Neddermeyer's discovery of the mesotron, just now brought prominently to the fore in all cosmic-ray discussions, and I have left unmentioned many pieces of work of equal importance with those I have discussed. I close my review of the last hundred years of physics with the discovery suggested by Einstein in 1905 but brought to fruition only in the 1940's.

The foregoing four discoveries of the period from 1895 to 1900 were followed in 1905 by Einstein's even greater discovery of the relation between mass and energy, namely, $E = mc^2$, $E$ being energy in ergs; $m$, mass in grams; and $c$, the speed of light in centimeters. This discovery suggested the possible answer to an age-old mystery—how the sun could have maintained his outflow of heat for billions of years when, if he were just a hot body cooling off, or even if he were made of carbon and oxygen in the proper proportion for burning, he could not possibly have maintained his heat output for more than a few thousand years. But the foregoing equation showed that if there were any way by which he could burn up his own mass, in view of the enormous size of the factor $c$ ($3 \times 10^{10}$ cm), he could maintain his present output of heat for very many billions of years. The physicists now feel very confident that this is exactly how the sun keeps his furnaces going, namely, by the conversion of a suitable portion of his own mass into radiant energy. This discovery outranks all others in its relation to the destiny of man, for if he can make this kind of a process take place on earth—and we now know that to a limited extent he can do so, as the atomic bomb in 1945 demonstrated—then he can at least destroy himself. It is possible also that he can use it only for beneficent purposes, so that it is not exaggerating to say that this is the most significant, the most fateful discovery that mankind has ever made. It was suggested as a possibility by Einstein in 1905, but first proved practically in 1945,[2] just at the end of the first century of existence of the AAAS.

[1] This states that in a given atom two electrons cannot occupy one and the same electronic position.

[2] I have discussed this discovery and its possible consequences at length in Chapter XVI, entitled "The Release and Utilization of Atomic Energy," in the last edition of a book published in 1947 by The University of Chicago Press.