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CHAPTER 11

TWENTIETH-CENTURY PHYSICS

What happened to physics at the beginning of the twentieth century? In many ways this seems a fairly straightforward example of a revolutionary change in science. The way of looking at the world now usually referred to as "classical physics" was superseded by the new theories of relativity and quantum mechanics. These new theories did not just suggest novel mathematical techniques for understanding nature or new ways of carrying out and interpreting experiments. They inaugurated completely new philosophical perspectives. The theories of special and general relativity required a wholesale rethinking of the relationship between space and time. Quantum mechanics called for a systematic reconsideration of the relationship between cause and effect, as well as a reassessment of just what it might be possible to know about the fundamental structure of matter. It is certainly the case that by the middle of the twentieth century, physicists were asking themselves questions about the ultimate nature of matter that would have been considered unthinkable—if not completely illegitimate—less than a century previously. The luminiferous ether—the focus of so much late nineteenth-century physical inquiry—was dead and buried. Nevertheless, as we shall see in this chapter, it is as easy to chart continuities as discontinuities between late nineteenth-century physicists and their concerns and those of their successors (see chap. 4, "The Conservation of Energy").

It is also certainly the case that massive institutional changes took place in physics during the course of the past century (see chap. 14, "The Organization of Science"). These institutional changes were very closely related to the new ways in which physicists started understanding the world around them, so much so that it is difficult to consider either aspect entirely separately. If the professionalization of physics (like other sciences) can be said to have started during the nineteenth century, then the process certainly accelerated during the twentieth century. At the same time, the process of specialization that started in the nineteenth century continued to the extent that by the middle of the twentieth century it was increasingly difficult to see physics even as a self-contained discipline. Theoretical and experimental physics (let alone subdisciplines, such as relativity theory, quantum mechanics, or particle physics) were becoming increasingly distinct from each other. This had important consequences for the practice and the content of physics. Physics and its subdisciplines were becoming increasingly esoteric, to the extent that physicists working in adjacent laboratories in the same institute might not fully understand what the other was doing. Physics also became a science that was more and more dependent on massive resources. Experiments at the end of the nineteenth century—and even up until the 1930s—could fit onto a tabletop. By the 1950s and 1960s the scale of things had changed completely, with physicists talking about the size of their apparatuses in kilometers rather than meters.

We will start this chapter back in the 1890s when J. J. Thomson carried out the experiments that would later be hailed as the "discovery of the electron." Those experiments, as well as those that led to the discoveries of X-rays and radioactivity, opened up a whole new set of problems for physicists. At the same time, they provided them with the tools with which to set about solving them. The result was a new understanding of the structure of the atom. The publication of Albert Einstein's theory of special relativity, closely followed a few years later by his theory of general relativity, provided another set of powerful tools and concepts for rethinking the structure of the universe. Again though, as we shall see, the significance of Einstein's insights took a while to sink in. It was not as clear to his contemporaries that his theories were as revolutionary as they might appear with the benefit of hindsight to us. Niels Bohr's quantum theory of the structure of the atom, incorporating the idea that energy was exchanged at the atomic level in discrete packages (or quanta) was a breakthrough too. Nevertheless it was dissatisfaction with this model (not least on Bohr's own part) that led to the development of quantum mechanics during the 1920s. After the Second World War, attention turned to probing ever more deeply into the structure of matter, with a resulting proliferation of elementary particles. Discovering and tracking these new particles required massive resources, consequently turning particle physics into the ultimate big science.

Inside the Atom

For much of the nineteenth century, atomic theory—the idea that matter should be considered as being made up of discrete, fundamental atoms—was very much a theory. As far as many physicists were concerned, atoms were at best a useful hypothesis, not to be taken as real existing objects. They provided chemists with a convenient way of balancing the books in chemical reactions but that was all (see chap. 3, "The Chemical Revolution"). It also seemed to many that inquiry into the fundamental structure of matter—to find out of it was made up of discrete units like atoms or was continuous and indefinitely divisible, for example—was beyond the scope of experiment. Theories about the structure of matter could in the end be nothing more than just theories. From the late 1850s, however, it seemed to some investigators, such as the German Julius Plücker, or William Robert Grove and John Peter Gassiot in England, that their experiments with discharge tubes provided new insights or, at least, new tools for investigating, the ultimate structure of matter. In experiments like these, in which currents of electricity were passed through attenuated gases in sealed tubes (a little like modern neon light tubes), strange glows appeared. The experimental physicist William Crookes, during the 1870s, argued that these cathode rays, as he called them, provided a new way of understanding the basic makeup of matter (fig. 11.1). By the 1880s, cathode ray experiments were part of the standard repertoire of physicists' experimental research.

One place where cathode ray experiments were taken up with enthusiasm was Cambridge's Cavendish Laboratory under the directorship of the physicist J. J. Thomson (fig. 11.2). Starting in the mid-1880s, Thomson himself began experimenting with gaseous discharges, looking for ways of investigating the relationship among matter, electric fields, and the ether. He also wanted empirical evidence for his model of matter as being made up of interlocking vortices in the ether. In 1897, Thomson announced that his latest experiments of cathode rays showed that they were made up of a stream of small negatively charged particles, each of which had a mass of about a thousand times smaller than a hydrogen atom—usually regarded at the time as the smallest unit of matter. He did this by means of measuring the ratio of electric charge to mass by deflecting the cathode rays in a magnetic field and, in later experiments, in an electrostatic field as well. He also suggested that his particles, or corpuscles, were the components from which atoms of matter were made. Such ether theorists as Joseph Larmor and George FitzGerald suggested that the corpuscles that Thomson had

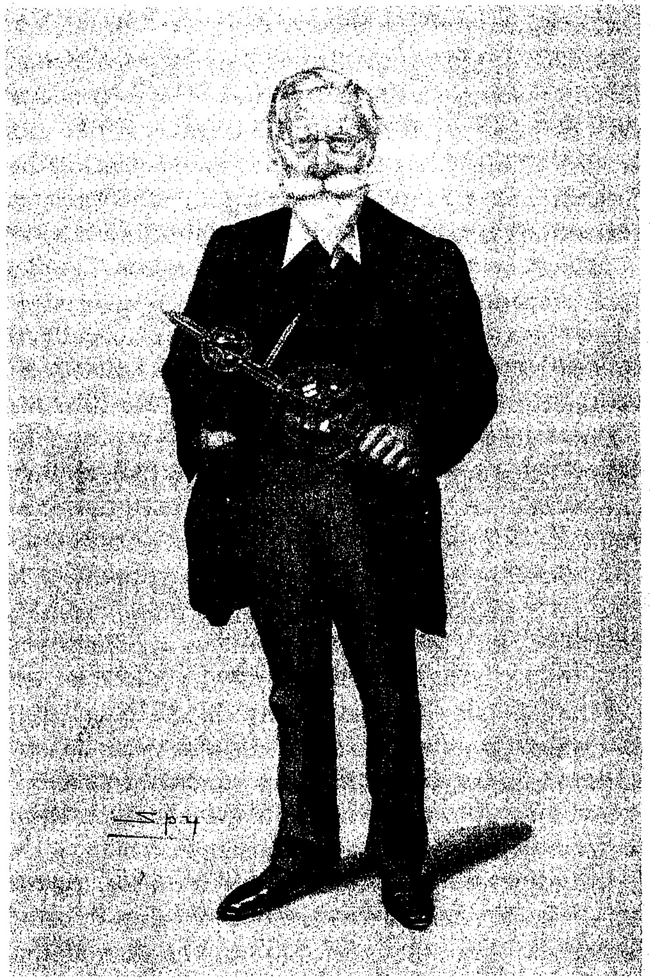

FIGURE 11.1 A cartoon of William Crookes holding a cathode ray tube, from *Vanity Fair* (image courtesy of the Science and Society Picture Library, London).

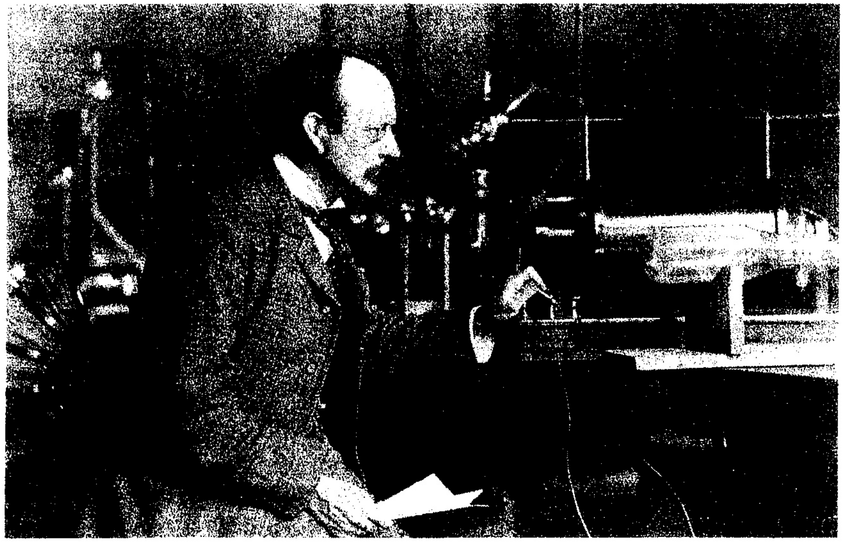

FIGURE 11.2 J. J. Thomson at the Cavendish Laboratory in Cambridge, working with the apparatus he used in the discovery of the electron in 1897. Photo courtesy of the Department of Physics/Cavendish Laboratory, University of Cambridge).

identified were "electrons"—a word that Larmor had coined some years earlier to describe packets of pure electrical energy in the ether. One reason that they suggested this was because they were unhappy with Thomson's suggestion that his corpuscles, rather than atoms, were the ultimate constituents of matter.

A year before Thomson's announcement, the German physicist Wilhelm Röntgen had claimed the discovery of an entirely new kind of ray—soon dubbed X-rays. Like Thomson, he had made his discovery while experimenting with cathode rays from discharge tubes; in fact, it was as a result of Röntgen's work that Thomson commenced his own cathode ray experiments. The new X-rays appeared to have some amazing properties. They seemed to pass through solid objects as if they were sheets of transparent glass. Röntgen himself quickly discovered their use in taking photographs of the inside of the human body, publishing a photograph of the skeletal structure of a hand. Investigators were soon experimenting to understand the properties of the new rays. They could be reflected and refracted like beams of light but not, it seemed at first, diffracted. One of these experimenters, Henri Becquerel, soon came up with another new kind of ray, seemingly emanating from uranium salts. Inspired by Becquerel's discoveries, the Sorbonne student Marie Curie and her husband Pierre turned to study these new radiations as well. In 1898, they announced the existence of two new "radioactive" elements, polonium and radium, which gave off these new kinds of rays in copious quantities. The Curies argued that the source of the radioactivity seemed to be inside the atoms of their newly discovered elements.

As with X-rays, experimenters set out to investigate the properties of this mysterious radiation. Becquerel succeeded in deflecting it in a magnetic field, suggesting that it had negative charge. Thomson succeeded in measuring its charge to mass ratio, suggesting it was close to that of cathode rays. Thomson's student at the Cavendish, the New Zealander Ernest Rutherford, soon found that there was more than one kind of this radiation. Different kinds of radiation were stopped by different thicknesses of aluminum foil. Alpha rays were relatively easily stopped; beta rays were more persistent. The Frenchman Paul Villard showed in 1900 that there was an even more penetrating kind of ray—gamma rays—that seemed to pass through everything. By the early 1900s, Rutherford and his colleague Frederick Soddy were arguing that radioactivity seemed to emanate from inside the atom and—even more controversially—that in the process elements changed into other elements. Radioactivity appeared to be a source of energy from inside matter itself. It was soon suggested that it was the ultimate source of the sun's energy. It was established that beta rays were streams of Thomson's electrons. Rutherford suggested in 1905 that alpha rays were streams of positive ions of helium. Now based in Manchester, Rutherford used scintillation screens to count individual particles of radiation and worked at measuring their deflections in different magnetic and electric fields. Increasingly, it looked as if studying the new particles could unlock the secrets of the atom's interior.

In 1911 Rutherford announced his model of the atom, based on his latest experiments. He had been investigating the ways that alpha particles were scattered when passed through thin metal foil by looking at scintillations on a phosphorescent screen. These were difficult and sensitive experiments involving long hours of observing tiny flashes of light through a microscope in a darkened room. They also depended on access to the difficult-to-get radioactive sources. Only those with a secure supply of the precious radium could engage in such an enterprise. In the course of Rutherford's experiments it seemed as if some of the alpha particles bounced back off the metal foil. Rutherford was sure that each individual deflection was the result of a single interaction between an alpha particle and an atom. The alpha particles bouncing back from the foil must have done so as a result of having encountered a large and concentrated positive charge. This was the

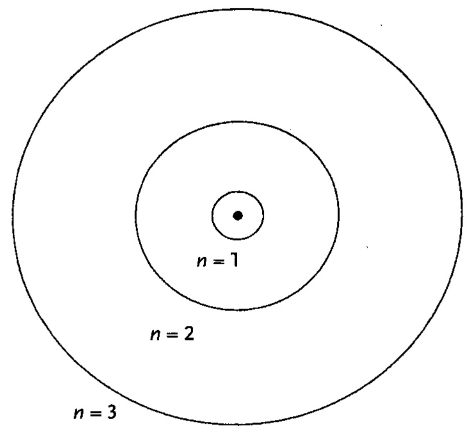

FIGURE 11.3 Niels Bohr's model of the hydrogen atom in which an electron could only orbit the central nucleus in orbits defined by Planck's Constant, *h*.

evidence on which he based his new model of atomic structure. He suggested that atoms were made up of a relatively large, positively charged core—the nucleus—surrounded by a number of relatively small orbiting electrons, just like the planets orbiting around the sun. Though seemingly simple, the model was not without its problems. In particular, Rutherford's model seemed to be unstable. According to physicists' understanding, the electrons orbiting the central nucleus should radiate energy as they did so. However, as they radiated energy they should also lose momentum and quickly end up spiraling into the central core. In other words, according to Rutherford's model, atoms should not exist—at least not for very long.

A young Danish physicist, Niels Bohr, suggested a solution to this problem. Bohr had worked with Thomson at the Cavendish and with Rutherford at Manchester. In 1913, Bohr suggested a model of atomic structure very similar to that proposed by Rutherford, but with one important difference. Bohr suggested that the electrons orbiting the central nucleus could only release their energy in distinct packets of energy, each with a distinctive frequency (fig. 11.3). This was how he solved the problem of atomic stability. The electrons orbiting the nucleus were not radiating continuously, they only did so at particular frequencies. Bohr was picking up on an idea first formulated by the German physicist Max Planck (of whom more later in this chapter) that energy could be released in quanta (i.e., discrete packets) defined by a constant factor—called Planck's constant (*h*) after its inventor. Albert Einstein had already made use of Planck's constant to argue that light could be treated as particles, each with an energy defined by the light frequency multiplied by *h*. What Bohr suggested was that atoms could exist in a number of stable states, each defined as a multiple of *h*. They only released energy when they changed from one state to another, and the energy they released in that process was a multiple of *h* and their change of frequency.

One crucial feature of Bohr's model of atomic structure was that it provided an explanation for the distinctive emission and absorption spectra of the different elements. It had been known for decades that the elements had distinctive spectra like this—different elements showed distinct dark lines in particular parts of the spectrum. This was how physicists used spectroscopy to identify the elements making up different substances: by comparing a sample to known elements and comparing their spectra they could use the spectral lines to identify the unknown elements. According to Bohr's model, this was because the individual atoms making up an element only vibrated at particular frequencies, corresponding to the spectral lines. In particular, Bohr's model explained Balmer's formula—an empirically derived formula worked out by the Swiss mathematician Johann Balmer showing that the position of these lines in the spectrum followed a regular pattern. Bohr managed to show that his equations fit the Balmer formula as well. The Rydberg Constant governing the relationship between the spectral lines was shown by Bohr to be itself a derivative of Planck's constant. Bohr had succeeded in bringing together the theory of discontinuous radiation pioneered by Planck and Rutherford's model of atomic structure. There was only one problem with the theory. It violated most of the then accepted laws of physics. British physicists such as Lord Rayleigh—J. J. Thomson's predecessor at the Cavendish—were unhappy with the introduction of the mysterious quantum. German theoretical physicists who had accepted Planck's views on the quantum of energy were unhappy with the idea that the atom was a real entity, let alone one whose physical structure could be discovered (Pais 1991).

Redefining Space and Time

One of the outstanding questions of late nineteenth-century physics was the issue of the earth's movement relative to the luminiferous ether. According to some theories it should be possible to detect the earth's movement through the ether by measuring differences in the velocity of light. To put it simply, when the earth was moving toward the light source, light should appear to be moving slower; when the earth was moving away

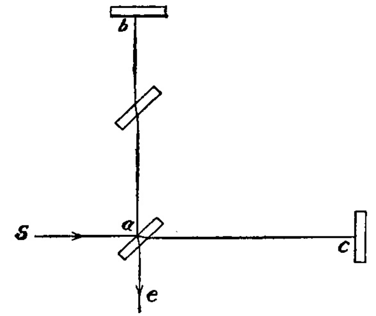

FIGURE 11.4 A diagram of the Michelson-Morley apparatus used in an attempt to measure the earth's movement through the ether. If the earth (and therefore the apparatuses) moved through the either, then the two beams of light aiming at the detector should arrive there slightly out of phase, causing an interference pattern, since one beam would have traveled slightly faster than the other. Michelson and Morley failed to detect any interference.

through the ether, light should appear to be faster. In 1888, two American physicists, Albert Michelson and Edward Morley, published the results of their experiments showing that they could detect no such deviation in the speed of light (fig. 11.4). Historians, philosophers, and physicists have often presented the experiment as a decisive refutation of the ether's existence. We will return to this point later. For the moment it should be enough to say that no physicist at the time—including the experimenters themselves—took it to be any such thing. At worst it was a problem to be solved, at best, to some it was even a potential confirmation of their own versions of ether theory. The extent to which the Michelson-Morley experiment played any role in the theoretical ruminations of the young Albert Einstein also remains a matter of considerable dispute, to which we will return again.

In 1905, when Albert Einstein published his paper on "The Electrodynamics of Moving Bodies" in the *Annalen der Physik,* he was an obscure patent examiner in Zurich, having graduated from the Zurich Polytechnic a few years previously. He had a handful of publications under his belt, but nothing to indicate that he was about to turn the world of physics on its head. In his 1905 paper, Einstein introduced two new principles into physics that led eventually to a completely new understanding of the nature of space and time. According to his principle of relativity, there was no privileged, absolute perspective from which to view events in the universe. All movement could only be measured relative to some particular frame of reference. Everything was relative—except for the velocity of light, which remained the same in all frames of reference. This was the second principle—the constancy in all frames of reference of the velocity of light. There was no such thing as Newtonian absolute space or absolute time according to this model. It turned out from Einstein's calculations that time itself was relative within this framework. Time as experienced within one frame of reference proceeded at a different rate from time as experienced from a frame of reference moving at a different velocity. In other words everything in Einstein's universe was relative.

Einstein's theory did not appear entirely from nowhere. The Dutch physicist Hendrik Antoon Lorentz had proposed the existence of a contraction effect in electrical charges moving at high velocities as a way of accounting for slight variations in the forces they exerted on one another. The Irish physicist George FitzGerald had made a similar suggestion. FitzGerald also suggested that this contraction effect accounted for Michelson and Morley's failure to measure the motion of the earth relative to the ether. According to FitzGerald, the contraction effect neatly counterbalanced the expected difference in the measured velocity of light. The mathematical equations translating the apparent dimensions of an object moving at one velocity from the perspective of someone at rest (or moving at a different velocity) were known as the Lorentz-FitzGerald transformations. In fact, questions like these to do with the electrodynamics of moving bodies (the title of Einstein's paper) were very much at the forefront of theoretical work on the properties of the ether, particularly by Cambridge-trained mathematical physicists such as FitzGerald or Joseph Larmor. What turned out to be different about Einstein's work, however, was the way in which he used electrodynamical calculations to propose a radical break not only with the ether but also with the Newtonian perspective that space was absolute.

Reactions to Einstein's new theory were mixed and slow in coming. To some commentators there appeared to be relatively little new in his formulation. It was certainly very easy for British-trained mathematical physicists to regard Einstein's contribution as just another paper on the electrodynamics of moving bodies, albeit possibly one written in unnecessarily obscure language. The science magazine *Nature,* for example, mentioned Einstein's views on relativity in the same breath as those of Larmor and the ether theory's foremost champion, Sir Oliver Lodge. German-trained theoretical physicists, more sympathetic to the tradition of research in which Einstein had been taught, were more receptive to the possibilities that his

theory of relativity opened up. Einstein himself published a series of papers over the next few years, expanding and refining his theory. One of these supplementary papers contained his first proofs of the famous equation linking mass and energy, stating that the energy of a body is equal to its mass multiplied by the square of the speed of light. One of the first to respond positively to Einstein's theory was Max Planck, who presented a seminar on Einstein's theory at Berlin in 1905–6. In 1908, Hermann Minkowski, a former teacher of Einstein's at Zurich, gave a lecture at Göttingen in which he started to develop a simplified mathematical approach to relativity and introduced the possibility of expressing the relationship between space and time in terms of non-Euclidean geometry.

In 1907, Einstein published a review paper outlining work on the theory of relativity over the previous two years. In this review paper, he first raised the possibility that the scope of relativity theory might be expanded to consider systems undergoing relative acceleration as well as systems moving at constant velocities with respect to each other. He also suggested that relativity might be expanded into a theory of gravitation. It took him and others until 1915 to work out fully the implications of these suggestions and to produce what is now known as Einstein's general theory of relativity. According to Einstein's fully fledged theory, the principle of relativity did indeed apply to systems that were accelerating relative to each other. With the help of Marcel Grossman, a professor colleague at the Zurich Polytechnic, Einstein also developed a mathematical way to apply Minkowski's suggestions concerning non-Euclidean geometries of space and time to the theory of gravitation. They found a way to describe gravitation in terms of the curvature of space-time. Einstein's theory also suggested that the spectrum of light should shift toward the red end of the spectrum under the influence of a gravitational field. Another suggestion famously predicted that light rays would curve under the influence of gravity. In Minkowskian terms, light would continue to follow the shortest route between two points, but under the influence of gravity, space itself would be curved and so the shortest route that light could follow would be curved, too. General relativity also suggested that an observer would experience time differently in gravitational fields of different intensities.

One virtue that Einstein as well as other physicists saw in the general theory of relativity was that it appeared to be open to straightforward empirical confirmation. Einstein himself had already demonstrated that the theory could be used to account for anomalies in the orbit of Mercury that could not be explained using Newtonian gravitational theory. The real breakthrough came, however, when the British astronomer and enthusiast for general relativity Arthur Eddington announced his intention to test Einstein's prediction of light bending in a gravitational field during the forthcoming solar eclipse of 1919. Eddington aimed to use the opportunity of the eclipse to photograph the positions of stars around the sun's corona that would normally be obscured by the sun's light. By comparing their positions with those they appeared to occupy when the sun was not in their portion of the sky he could then determine whether light bending occurred as a result of the sun's gravitational field. The result was trumpeted as a stunning success for Einstein and general relativity theory. It was this decisive-seeming confirmation of his theory that made Einstein into a household name as newspapers across Europe and America splashed reports of the joint meeting of the Royal Astronomical Society and the Royal Society at which the announcement was made across their leading pages.

A great deal of ink had been spilled by historians, philosophers, and physicists alike over the issue of the relationship between Einstein's theories and their apparent empirical confirmations. One important focus of controversy has been the role of the Michelson-Morley experiment in Einstein's thinking leading up to the announcement of his special relativity paper. That paper makes no mention of the experiment, and Einstein in later years gave contradictory accounts of whether he had been aware of Michelson-Morley at the time. The experiment is nevertheless frequently cited as a decisive factor in the formulation and reception of relativity theory. It is also cited as a decisive refutation of the ether, with the efforts of ether theorists to accommodate it into their theoretical frameworks derided as clumsy post hoc rationalizations. Another focus of controversy is the role of Eddington's eclipse observations. Historians and philosophers have argued that the data Eddington and others provided as, in point of fact, ambiguous. They could have been interpreted differently so as to support classical Newtonian theory (which also predicts some light bending) rather than general relativity (Earman and Glymour 1980). What matters for the historian in cases like these is how the relevant information was used at the time, rather than how it might (or should) have been used—in which case, the Michelson-Morley experiment was clearly not decisive, while the Eddington observations were.

The relatively rapid acceptance of Einstein's theories—in some circles at least—is frequently described in terms of a decisive refutation of ether theory. As we just mentioned, the Michelson-Morley experiment is usually described as having struck the first blow, while Einstein's theory delivered the

coup de grâce. As we have seen, however, the reality was rather more complex. Some ether theorists positively welcomed the Michelson-Morley results as confirmation of their versions of ether theory. This was how some contemporaries understood Einstein's theory initially as well. It was another theory that seemed to support the view of some theorists that the earth's motion through the ether could not be measured. What were more decisive in the reception of Einstein's theories were the changing institutions of physics itself. The tradition of mathematical physics, as taught at Cambridge, for example, was dying out. The newer German tradition of theoretical physics was in ascendancy (Jungnickel and McCormmach 1986). To the increasing numbers of physicists turning to new German theoretical practices and techniques, Einstein's theories looked more promising than the antiquated approaches of the previous generation. New physics research institutes—again predominantly in Germany and in countries that had adopted the German approach to physics—were also producing a new generation of physicists trained in the highly sophisticated and difficult to master mathematical techniques that Einstein adopted. To this new generation, Einstein's approach and that of others like him seemed more familiar, more powerful, and more promising.

The Uncertainty Principle

In the same year that Einstein published his paper on special relativity he also published another ground-shaking contribution, this time on the anomalous behavior of light. It was known that shining a beam of light onto certain substances caused some kind of electric emission. Hertz had noticed the phenomenon in 1887 during the course of the experiments that would lead him to electromagnetic waves (see chap. 4, "The Conservation of Energy"). In 1899, J. J. Thomson suggested that this photoelectric effect was the result of a stream of electrons being emitted from the substance. One peculiar feature of this photoelectric effect was that it seemed to depend on the frequency rather than the intensity of the beams of light. Hertz had noted that the phenomenon seemed to be a property of ultraviolet light, in particular. What Einstein suggested in his 1905 paper was that this phenomenon could be understood by assuming that under these circumstances light acted like a particle rather than a wave. He could then show that the energy required to make one electron leave the surface of the metal was given by the frequency of the light multiplied by a constant. It was as if light traveled in packets, each carrying just that amount of energy. When these light quanta, or photons, struck an electron, that energy was transferred to it.

The constant in Einstein's equation was Planck's constant, which we first encountered a few paragraphs ago. The physicist Max Planck had invented the number in the course of his investigations of the phenomenon of black body radiation. A black body was a theoretical construct that absorbs and emits radiation at all frequencies. The physicist Wilhelm Wien, during the 1890s, worked out the equations that dealt with this hypothetical situation by treating the radiation as an example of thermal equilibrium and applying the laws of thermodynamics, particularly those relating to entropy. As experimenters began to produce experimental set-ups that approximated a perfect black body; however, it started to become clear that the experimental data did not fit. Lord Rayleigh and James Jeans developed an alternative formulation that worked well for low frequencies of radiation but at higher frequencies was prone to the "ultraviolet catastrophe": the energy released was a function of the square of the frequency, which meant that at higher frequencies (like that for ultraviolet light) it veered toward infinity. Planck succeeded in producing his own solution to the problem that avoided the ultraviolet catastrophe at the expense of what looked to many like a deeply unsatisfactory fudge. He had to assume that the energy was released in packets depending on the frequency of the radiation multiplied by a constant factor. That factor was Planck's constant—what he called the quantum of action.

As we have seen already, Niels Bohr made good use of Planck's quantum of action when he was putting together his model of atomic structure. Bohr used Planck's constant to help define the different energy states in which the electrons orbiting the central nucleus of an atom could remain stable. Despite the model's success in explaining the empirical data derived from experiments such as those carried out by Rutherford at Manchester, as well as its heuristic value in suggesting new theoretical developments, many physicists—Bohr himself included—felt deeply unsatisfied with it. The problem was simple. It seemed that the Bohr model—and the quantum theory built around it—was a halfway house between classical physics and something else. The Bohr model was "classical" in that it largely followed the rules and assumptions of Newtonian mechanics. The atom consisted of discrete particles—electrons—orbiting a central core—the nucleus—in well-defined orbits. The only difference was that they could change orbits, indeed could change orbits only, according to principles that violated fundamental mechanical principles. By the 1920s, Bohr and other physicists were actively trying to find new and foundational physical principles that

would allow them to make sense of quantum theory. Their problem was not with the physics of the Bohr model; it was with its metaphysics.

One of the first efforts to move toward an alternative formulation was the work of the young German physicist Werner Heisenberg. In 1924, Heisenberg spent six months in Copenhagen, carrying out research at the Institute for Theoretical Physics that Bohr had established. This kind of close collaborative working was to be crucial in the events that followed, as the key players met and worked together at colloquia, conferences, and research institutes. Frustrated by the ad hoc appearance of quantum theory, Heisenberg wanted to return to first principles and produce a completely new mathematical technology to deal with the phenomena. He wanted to do away with such theoretical concepts as atomic orbitals that had, in principle, no observable attributes. In his quantum mechanics (as he called it), Heisenberg replaced the notion of atomic orbitals with the assumption that atoms exist in different quantum states that can be mathematically defined. Following the suggestion of his mentor Max Born, Heisenberg used the mathematical notation of matrix calculus to express the different possible quantum states. At about the same time in Cambridge, another young physicist, Paul Dirac, was working toward a similar theory. Heisenberg and his allies were quite self-consciously jettisoning the trappings of classical physics and trying to base their procedures on a wholly new observational foundation.

A different approach to the anomalies of quantum theory was also being developed based on the suggestion of the young French aristocrat Louis de Broglie. Inspired by Einstein's suggestion in his 1905 paper that light occasionally behaved like a particle, de Broglie suggested in 1923 that under certain circumstances it might be possible to treat particles (electrons specifically) as if they were waves. He suggested that the electrons orbiting a nucleus could be described as existing in a stationary wave with the different possible orbitals then being defined as the range of possible frequencies at which that stationary wave could oscillate. The suggestion was taken up and expanded a few years later by the Viennese physicist Erwin Schrödinger. Schrödinger's particular achievement in his formulation of wave mechanics (as he called his theory) in 1926 was to derive a wave equation for the hydrogen atom, showing that it was possible to calculate stationary wave states that corresponded to each of Bohr's orbital levels. Where Heisenberg saw himself as quite self-consciously doing away with classical physics, Schrödiger regarded his wave mechanics as a continuation of the classical tradition. It was clear, however, that, as the physicist Wolfgang Pauli argued and Schrödinger acknowledged, wave mechanics and quantum mechanics were, formally at least, different but equivalent mathematical expressions of the same state of affairs. What remained unclear was just what that state of affairs was.

Schrödinger himself offered one early response to the question of how to interpret this new physics. He suggested that the wave packets described by his theory held together over time and that particles should be visualized as simply being tightly held together wave packets. In that case, there was no discontinuity between classical and wave mechanics. A more radical interpretation was offered by Max Born. In his view, the best way to understand quantum mechanics was by invoking statistics. In a paper published in 1926 on the quantum mechanics of a beam of particles being scattered by a center of force, Born suggested that the best way to interpret the equations was as expressions of probabilities. In other words, what his equations showed in terms of the effect on individual particles colliding with the center of force was not what happened but what probably happened. Where Schrödinger wanted to preserve the link with classical approaches by ditching particles, Born wanted to preserve the usefulness of particle-based physical explanations while defining a concrete meaning for wave equations. His conclusion was that the wave equations were expressions of probability distribution. Increasingly, battle lines were being drawn up around this issue: What did quantum mechanics mean? What kind of picture of the world did it project?

The protagonists gathered in Copenhagen in 1926 and 1927. Bohr, Schrödinger, and Heisenberg met in October 1926 when Schrödinger gave a lecture there at Bohr's invitation on the foundations of wave mechanics. Heisenberg had already heard him give a similar talk in Munich and was horrified by his attempts to produce a classical interpretation of quantum mechanics. Schrödinger was likewise unimpressed by Bohr's and Heisenberg's leaps between quantum states and Born's probability interpretation. Heisenberg was back in Copenhagen in early 1927, still working on a satisfactory physical interpretation of the new physics. The result was an abandonment of the laws of classical causality and the establishment of the uncertainty principles. According to Heisenberg, it was not possible in the quantum world to state definitively that a particular state of affairs would definitively cause another state of affairs. Before the event, all that could be known were probabilities. This was because there were limits as to what could, in principle, be known about any state of affairs. It was impossible to know both the location and the momentum of a particle with equal precision. Similarly, it was impossible to know the energy state of an object and the time at which it was in that state with equal precision. The focus was on the observable phenomena. Bohr's way of putting it was that the question of whether an electron was a particle or a wave was no longer relevant. What mattered was whether and under what circumstances it behaved like a particle or a wave.

The Copenhagen interpretation was and remains controversial. Schrödinger never accepted it—hence the famous paradox of Schrödinger's cat. In this paradox, Schrödinger described a hypothetical experiment in which a cat, confined in a box, was subjected to a process that either would or would not kill it, depending on the outcome of a particular event at quantum level, such as a vial of poison being released only if it was triggered by the emission of a single electron from an atom. According to the Copenhagen interpretation, the decisive quantum event could not meaningfully be said to have taken place until its outcome was actually observed. Until then, all that could be said was that there was a superposition of quantum states. But that would mean that until somebody opened the box and looked inside, the cat could not meaningfully be said to be either dead or alive. It would exist in a superposition of states, both dead and alive. Schrödinger regarded this as a reductio ad absurdum argument, revealing the inherent absurdity of the Copenhagen position (Wheaton 1983; Darrigol 1992).

Another famous dissident was Albert Einstein, who never accepted that quantum mechanics was really "the secret of the Old One . . . that *He* does not play dice." Some historians have argued that the wholesale rejection of classical notions of causality that underpinned the Copenhagen interpretation can be traced to the cultural pessimism of postwar Germany's Weimar Republic. According to this view, quantum mechanics should be seen in the same light as the philosophical, literary, and artistic rejection of classical forms of rationality that followed Germany's defeat in the Great War (Forman 1971). There is clearly some truth in the suggestion, though it does little to explain quantum mechanics' success elsewhere or its continued hold on contemporary theoretical physics. The explanation for that is more likely to lie—as we have argued it does for relativity theory—in the appeal of new, powerful, and esoteric mathematical technologies to a new (almost the first so trained) generation of theoretical physicists and in the power of the institutional traditions that generation established. It is also worth noting the relatively small size and the mobility of the group involved in founding quantum mechanics. They knew each other; they traveled constantly among each others' research institutions and met frequently at recently inaugurated international events, such as the Solvay Conferences. In that respect, quantum mechanics was successful precisely because it was a team effort.

Big Physics

By the 1920s, Ernest Rutherford, by then J. J. Thomson's successor as director of the Cavendish Laboratory in Cambridge, was well-established as one of the world's foremost investigators of the atom's interior. The apparatus he and his coexperimenters used was—by the modern standards for such experiments with which we are more familiar today—deceptively modest and simple. Rutherford and his team bombarded sheets of metal foil with radiation from a radioactive source such as radium. Their goal was to find out how the path of the radiation changed as it passed through the foil so they used phosphorescent screens to capture the individual scintillations as the particles of radiation struck. The problem with studying the trajectories and properties of these subatomic particles was simple—how to detect them? Rutherford's Manchester colleague Hans Geiger had developed a number of different techniques to record the incidence of radiation. Working at the Physikalisch-Technische Reichsansalt after 1912, he developed what became known as the Geiger counter for counting alpha particles. The Cambridge graduate C. T. R. Wilson developed another important device. In the process of trying to produce artificial clouds in the laboratory, he found that tiny drops of water would collect around individual ions, leaving a visible trace. Using Wilson's cloud chambers, as they were called, it was possible actually to trace the movements of individual particles of radiation.

Maybe the greatest triumph of the Cambridge school of nuclear physicists that built up around Rutherford was James Chadwick's identification of a new subatomic particle—the neutron. In 1928, the German physicists Walter Bothe and Herbert Becker had found that when a sample of the metallic element beryllium was bombarded with alpha particles, it gave off an electrically neutral radiation, which they took to be gamma rays. A few years later in 1932, Irene Joliot-Curie (Marie Curie's daughter) and her husband Frederic found that this radiation caused protons (positive subatomic particles, taken at the time to be one of the constituents of the nucleus along with equal numbers of electrons) to be emitted from a paraffin target. Chadwick repeated the Joliot-Curies' experiments using other elements as well as targets. By comparing the energies of the charged particles emitted

by the different targets he concluded that the electrically neutral radiation was not gamma rays but a stream of neutral particles of approximately the same mass as the proton. This was the neutron. Not only did the discovery—for which Chadwick won the Nobel Prize in 1935—provide more information about the structure of atoms, it also provided a powerful new tool for further research. Being electrically neutral, streams of neutrons were highly penetrative and could be used to delve even further into the atom's heart.

In 1928 the Soviet physicist George Gamow published an explanation of alpha particle radiation in terms of quantum mechanics. It was one of the first efforts to apply the new tools of theoretical physics to understanding the subatomic particles and processes that the radioactivists had been investigating for the past decade. Gamow showed that alpha particle emission was not the result of some random and arbitrary instability in the atomic nucleus but a straightforward consequence of the laws of quantum mechanics (an effect now known as quantum tunneling). During the 1930s, theoretical physicists were increasingly interested in finding ways of interpreting the new information provided by nuclear physicists—particularly the new information about the interior of the nucleus that could be gleaned using the newly discovered neutron. Heisenberg suggested that the contents of the nucleus were held together by a new kind of force, that these nuclear forces must act only at very short ranges, and that they were about a million times stronger than the electrostatic forces holding the atom together. From the mid-1930s onward, Niels Bohr elaborated his theory of the nucleus in which it was regarded as similar in many ways to a drop of liquid. Bohr and his co-worker Fritz Kalchar argued that just as drops of liquids vibrate when force is applied to them, so does the atomic nucleus, and that those different states of vibration could be regarded as quantum states.

With the outbreak of war, many nuclear and theoretical physicists found themselves working for their respective sides' war efforts. Heisenberg played a key role in Nazi efforts to produce nuclear weaponry. Einstein was one of the instigators of a letter to Franklin Roosevelt, the U.S. president, which was instrumental in bringing about the Manhattan Project. By the end of the Second World War, a great deal more was known about nuclear physics than at its outset. The bombings of Hiroshima and Nagasaki had made the consequences of splitting the atom terrifyingly explicit. On both sides, too, the war efforts had resulted in unprecedented resources in manpower and money being directed toward nuclear physics. For the first time, physics was starting to become a matter of large-scale collective effort (see chap. 20, "Science and War"). When nuclear physicists met at the Cavendish Laboratory in Cambridge in 1946 for their first conference since the beginning of the war, their field appeared to be booming. The number of elementary subatomic particles had certainly proliferated. The list now consisted of electrons, mesons, neutrons, neutrinos, photons, positrons, and protons. Mesons had been predicted by the Japanese physicist Hideki Ukawa in 1935 as a means of explaining the transmission of nuclear forces. They were identified in cosmic ray studies a few years later. Positrons (positively charged electrons) had been theoretically predicted by Paul Dirac at Cambridge and found at CalTech in the early 1930s. Neutrinos were hypothetical particles, invoked to preserve the conservation of energy in certain interactions involving beta particles. They were not universally accepted at first. Bohr initially preferred to abandon the principle of the conservation of energy rather than accept the existence of particles of whose existence there was no other evidence. By about 1936, however, he was leaning toward acceptance of the physical reality of neutrinos.

By the 1940s, experiments in nuclear physics were rapidly leaving behind the tabletops on which they were first carried out. Experimental apparatus during the 1920s and early 1930s was relatively small scale. The main piece of apparatus that Chadwick used in identifying the neutron was only six inches long. His was the last discovery of a subatomic particle to take place using apparatus like this. By the 1950s and 1960s, chasing subatomic particles needed massive equipment and equally massive investments of labor and money. The trend was well underway by the beginning of the Second World War. When the Italian physicist Enrico Fermi carried out the first controlled nuclear chain reaction of 1942, he needed a laboratory the size of a squash court (it was, in fact, a squash court beneath the University of Chicago's football stadium). After the war, Fermi became head of the Institute of Nuclear Physics at Chicago, where in 1951 he played a key role in developing their synchrocyclotron, a massive piece of equipment in which subatomic particles were accelerated to high velocities before hitting a target so that their properties and constitution could be studied. It was one of the first of a new generation of increasingly powerful experimental apparatuses. By the later 1950s, instruments like this were already several meters in diameter. It was this kind of experiment that was starting to make terms such as "elementary" or "fundamental" increasingly dangerous words in particle physics.

By the early 1960s, two kinds of elementary particle were generally recognized. There were hadrons—particles like protons and neutrons that made up the nucleus—and leptons—like electrons. By 1964, however, this picture was starting to fall apart. Experiments with ever more powerful particle accelerators seemed to suggest that hadrons were not elementary particles after all. They were made of other particles, eventually dubbed quarks. The suggestion was first made on theoretical grounds by an American physicist, Murray Gell-Mann, working at the California Institute of Technology, along with the Russian-born George Zweig, then working at the Conseil Européen pour la Recherche Nucléaire Laboratory in Switzerland. There were three kinds of quarks: "up," "down," and "strange" quarks. Different combinations of quarks came together to produce the range of hadrons. Quarks rapidly became very useful theoretical entities. They could be used to explain a great deal about the different quantum states of nuclear particles. The question of whether quarks really existed was nevertheless a matter of considerable debate. Many physicists argued that quarks were simply useful ways of organizing information rather than being real physical objects. Part of the problem was that quarks were difficult to find, despite the fact that given their properties—particularly the fact that they were supposed to have fractional electric charges—they should be relatively conspicuous. It was well into the 1970s before their physical reality was generally accepted (Pickering 1986).

The kind of physics that produced quarks was increasingly esoteric and technical. It also needed massive resources. The European contribution to particle physics by the 1950s needed international cooperation. The CERN particle accelerators built in Switzerland near the border to France were (and still are) literally huge enterprises, with instruments several kilometers in diameter. These massive enterprises have also required massive manpower. By the early 1960s, it is estimated that there were about 685 practicing particle physicists in Europe and an additional 850 in the United States. By the 1970s, the European figures had more than quadrupled and the American figures had doubled. Such projects were matters of national prestige as well. Successive American and European governments throughout the 1960s and 1970s poured increasingly large amounts of money into high energy particle physics (fig. 11.5). This was a very far cry from Rutherford's or Chadwick's tabletop experiments at the Cavendish Laboratory a half-century or so previously. High-energy particle physics was collaborative science par excellence. It also came to manifest a high degree of separation between experimenters and theoreticians. Where J. J. Thomson or the Curies at the beginning of the twentieth century combined theory and experi-

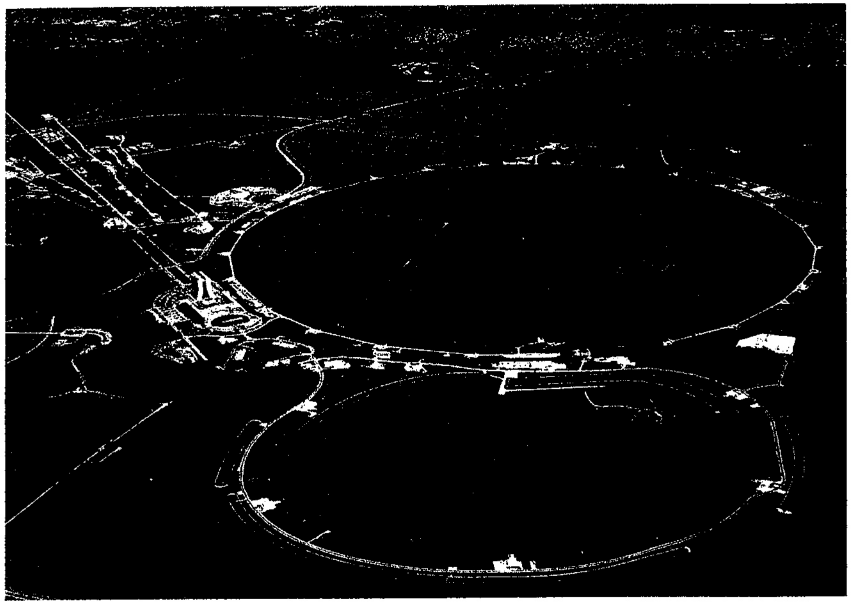

FIGURE 11.5 The site of a late twentieth-century particle accelerator (courtesy of Fermilab, Batavia, IL). Comparing this picture with the apparatus illustrated in fig.11.2 gives a graphic example of the change in scale in experimental physics over the intervening century.

ment in their activity, that combination became increasingly rare during the second half of the century. Doing theory or doing experiments came to require wholly different kinds of expertise.

Conclusions

The founders of relativity theory and quantum mechanics at the beginning of the last century certainly regarded themselves as engaged in a revolutionary process. They were overturning classical physics and replacing it with a wholly new intellectual edifice. In many ways, though, it was precisely through this dismantling that the idea of classical physics as a coherent and self-contained body of thought was established in the first place. It was defined as being what the new physics was not. This rift with the past was not, however, as inevitable or clear-cut as some of its proponents, at least, argued. We have seen that there were clear continuities between developments in relativity and quantum theories and previous approaches. Some of the new physics' own founders had mixed feelings about the abandonment of the old certainties. As we have seen, both Einstein and Schrödinger, for example, never reconciled themselves entirely to the withdrawal of physics from causality. Even Niels Bohr was considerably more ambivalent about the prospect than was Heisenberg—the real enthusiast for uncertainty. Throughout the century, physics also became an increasingly esoteric practice (or more accurately, set of practices). Becoming a physicist required years of extended and dedicated training. This only seems unsurprising to us because this is the scientific culture we live in too. It is easy to forget that nothing like it had existed before. Physics became an increasingly fragmented business as well, with experimenters and theorists inhabiting different institutes and different worldviews. New specialisms, such as solid state physics, developed, which crossed over old boundaries between academic and industrial science.

It is clear, moreover, that it is impossible to separate out the intellectual and institutional stories of twentieth-century physics. The institutions where physics was practiced had a massive impact on what physics was. The kind of highly skilled, intensive, and mathematically abstruse practice that theoretical physics became during the course of the twentieth century depended entirely on the existence of intensive, specialized research, and training institutes where it largely took place. It was an activity that could not take place without the cadres of thoroughly trained, specialized, and dedicated professional physicists that such places produced. Experimentation, too, was no longer the province of an individual scientist with a small team of helpers and technicians. An experiment at CERN or Fermilab required the mobilization of hundreds, if not thousands, of scientific workers. Physics became big business during the course of the twentieth century, requiring resources on a hitherto unprecedented scale. The number of people calling themselves professional physicists swelled by orders of magnitude during the course of the century. This was not an incidental feature in the development of modern physics. Without those resources and institutions, physics as it was practiced simply would not have been possible. The institutional shape of modern physics was an indispensable prerequisite of its intellectual content.

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