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J. Robert Oppenheimer: Before the War

Although Oppenheimer is now best remembered for his influence during World War II, he made many important contributions to theoretical physics in the 1930s

by John S. Rigden

Fifty years ago this month, on July 16, 1945, an unearthly blast of light seared the predawn sky over the desert in New Mexico. The witnesses of this event included many of this century's most distinguished physicists. As they watched the boiling glare through their welding goggles, a sober reality bore into them: the nuclear age had begun. The chief witness—the person who had directed the atomic bomb project from its inception—was J. Robert Oppenheimer.

Oppenheimer was a rare individual. His intellectual acuity, diverse interests, frail physique and ethereal personality made him a man of legendary proportions. After World War II Oppenheimer became a public figure, known for leading the physicists who built the atomic bomb at Los Alamos Laboratory. His success as the director of the Manhattan Project provided him with a base of influence, and, for a time, he enjoyed the authority and power that were his.

Then, in June 1954, amid the anticommunism paranoia of McCarthyism, the U.S. Atomic Energy Commission (AEC) concluded that Oppenheimer had defects in his character and deemed him a national security risk. Albert Einstein and others at the Institute for Advanced Study in Princeton, N.J., where Oppenheimer was then director, declared their support for him. In October the trustees of the institute reelected him to another term as director, a position he then held until a year before his death in February 1967. Still, after the AEC's actions, Oppenheimer's slight frame became the depiction of a broken man.

Few historians have written about the Oppenheimer who invigorated American theoretical physics a decade before the war, which is unfortunate for two reasons. First, Oppenheimer became a physicist at the rarest of times, when the theories of quantum mechanics and nuclear physics were being formed, revising a great deal of traditional thought in the field. Second, although he is sometimes characterized as an underachiever, Oppenheimer had in fact made many significant contributions to several major areas of physical research before taking his post at Los Alamos.

Oppenheimer built the foundation for contemporary studies of molecular physics. He was the first to recognize quantum-mechanical tunneling, which is the basis of the scanning tunneling microscope, used to reveal the structure of surfaces atom by atom. He fell just short of predicting the existence of the positron, the electron's antiparticle. He raised several crucial difficulties in the theory of quantum electrodynamics. He developed the theory of cosmic-ray showers. And long before neutron stars and black holes were part of our celestial landscape, Oppenheimer showed that massive stars can collapse under the influence of gravitational forces.

To Physics from Chemistry

Like many physicists of his era, Oppenheimer studied chemistry first. "Compared to physics," he said, "[chemistry] starts right in the heart of things." As a freshman at Harvard University he realized that "what I liked in chemistry was very close to physics." So that spring, he submitted a reading list to the physics department and was granted graduate standing. He enrolled in many physics classes, but because his interests and coursework were very diverse, he claimed later to have received only "a very quick, superficial, eager familiarization with some parts of physics." He wrote: "Although I liked to work, I spread myself very thin and got by with murder; I got A's in all these courses which I don't think I should have." Whether that was true or not, Oppenheimer did gain valuable experience working in Percy W. Bridgman's laboratory—a privilege granted to him by virtue of his advanced standing. In the 1920s American physics was dominated by experimentalists such as Bridgman, who was among the first to investigate the properties of matter under high pressure and built much of the apparatus needed to do so. Thus, from his student experiences, Oppenheimer did not distinguish between experimental and theoretical physics, the latter being largely a European activity. "I didn't know you could earn your living that way [as a theoretical physicist]," he once said, looking back on his undergraduate days.

For this reason, as his graduation in 1925 grew near, he aspired to work under Ernest Rutherford, one of the greatest experimentalists of the century, at the Cavendish Laboratory in Cambridge, England. Rutherford had conducted the first trials to reveal that atoms contained extremely small, heavy cores, or nuclei. He was, however, unimpressed with Oppenheimer's credentials and rejected his application. Oppenheimer next wrote to Joseph John Thomson, another renowned experimentalist at the Cavendish. Thomson accepted Oppenheimer as a research student and put him to work in a corner of the laboratory, depositing thin films on a base of collodion. "I am having a pretty bad time," he wrote to a high school friend on November 1, 1925. "The lab work is a terrible bore, and I am so bad at it that it is impossible to feel that I am learning anything."

The ensuing winter was a dark time for Oppenheimer, but with the coming of spring, new possibilities became apparent. Rutherford, who took to Oppenheimer in person, introduced him to Niels Bohr when Bohr visited the Cavendish; through Patrick M. S. Blackett, a physicist at the Cavendish, he met Paul Ehrenfest of the University of Leiden. He also became friends with the influential Cambridge physicists Paul A. M. Dirac and Ralph H. Fowler. All these men were theoreticians and helped to broaden Oppenheimer's view of the field. Fowler was particularly perceptive. He advised Oppenheimer to learn Dirac's new quantum-mechanical formalism and apply it to band spectra, a melding of old and new knowledge as yet untackled.

Oppenheimer became absorbed in the problem and over the next few years developed the modern theory of continuous spectra. This work not only led to his first paper, it also marked the beginning of his career as a theoretical physicist. When Max Born visited the Cavendish in the summer of 1926 and suggested that Oppenheimer pursue graduate studies at the University of Göttingen, a center for theoretical physics, Oppenheimer readily accepted the plan. "I felt completely relieved of the responsibility to go back into the laboratory," he said to the philosopher Thomas S. Kuhn in a 1963 interview.

It was at Göttingen that Oppenheimer first became aware of the problems perplexing European physicists. "The science is much better [here]," he wrote to his friend Francis Furgusson in November 1926. At that time, Born, Werner Heisenberg and Pascual Jordan were all in Göttingen, formulating the theory of quantum mechanics. Born, a distinguished teacher, made Göttingen as good a place as any to learn the intricacies of the new theory. Oppenheimer learned fast. In December 1926, only four short months after he had applied to Göttingen, he sent an article, "On the Quantum Theory of Continuous Spectra," to the leading German physics journal Zeitschrift für Physik. This paper was in fact an abridged version of what would be his dissertation. After receiving his doctorate from Göttingen in March 1927, he spent the next two years, one in the U.S. and one in Europe, as a National Research Council Fellow.

During this period, Oppenheimer profited a great deal from his association with prominent European physicists of the day. "They gave me some sense and…some taste in physics," he told Kuhn. Still, the theoretical problems he investigated were primarily of his own choosing. Later, in the 1930s, perhaps because of his own laboratory experience, Oppenheimer worked closely with experimentalists, many of whom acknowledged that he understood their data better than they did.

Atoms and Molecules

The atom, once found to emit discrete spectra during transitions between energy states, gave the first indication that the physics of preceding centuries was inadequate. Thus, atoms and molecules provided a natural testing ground for the new theory of quantum mechanics and for Oppenheimer in 1927. His first major contribution was finding a way to simplify the analysis of molecular spectra. By interpreting spectra, physicists determine the structure and properties of molecules. But an exact quantum-mechanical description of even a simple molecule is complicated by the fact that the electrons and nuclei of the atoms making up that molecule all interact with one another.

Oppenheimer recognized that because of the great disparity between the nuclear and electronic masses, these interactions could be largely ignored. The massive nuclei respond so slowly to mutual interactions that the electrons complete several cycles of their motion as the nuclei complete a small fraction of their own. While on a vacation, Oppenheimer wrote up a short paper on the topic and sent it to Born. Born was aghast at the brevity of Oppenheimer's draft and churned out a 30-page paper, showing in detail that the vibration and rotation of the nuclei could be treated separately from the motion of the electrons. Today the Born-Oppenheimer approximation is the starting point for physicists and chemists engaged in molecular analysis. Later on, Oppenheimer determined the probability that one atom captures the electron of another atom. In keeping with the Born-Oppenheimer approximation, he showed that the probability is independent of the internuclear potential between the two atoms.

Oppenheimer in fact discovered another quantum-mechanical behavior, called tunneling, in 1928. Tunneling occurs under many theoretical conditions. An electron, for example, can escape from confines that normally sequester it if it behaves like an infinitesimal billiard ball. The time-honored example of tunneling is that which takes place when a nucleus expels an alpha particle during radioactive decay. Inside a uranium nucleus, both nuclear and electrostatic forces will restrict the motion of an alpha particle. Classically, it has no way to leave the nucleus. Quantum-mechanically, though, the alpha particle can tunnel through the surrounding barrier and slip away.

During the summer of 1928 physicists George Gamow and, independently, Edward U. Condon and Ronald W. Gurney first explained radioactive disintegration by means of tunneling. Textbook writers of today acknowledge this fact, but they also imply that these scientists actually discovered the phenomenon, which is not true. Several months earlier, in March, Oppenheimer had submitted a paper to the Proceedings of the National Academy of Sciences that considered the e›ect an electric field has on an atom. Classically, an atom can be dissociated only by an intense electric field. In the quantum view, however, a weak field can separate an electron from its parent atom because the electron can tunnel through the barrier that binds it. Oppenheimer showed that a weak electric field could dislodge electrons from the surface of a metal. Gerd Binnig and Heinrich Rohrer of the IBM Zurich Research Laboratory developed the scanning tunneling microscope based on this principle in 1982, 54 years after Oppenheimer had discovered it [see "The Scanning Tunneling Microscope," by Gerd Binnig and Heinrich Rohrer; SCIENTIFIC AMERICAN, August 1985].

Particles and Fields

Oppenheimer spent his final months in Europe, from January to June 1929, with Wolfgang Pauli at the Swiss Federal Institute of Technology in Zurich. After this apprenticeship, Oppenheimer's interests turned away from applications of quantum mechanics to more basic questions of physics. The timing for such a shift was perfect. That spring he received o›ers from the California Institute of Technology and the University of California at Berkeley; in both places, physical research was aimed at the forefront of basic questions. Robert A. Millikan, who coined the term "cosmic rays" in 1925, was at Caltech, and Ernest O. Lawrence, who invented the cyclotron in 1930, was investigating nuclear physics at Berkeley.

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Oppenheimer accepted both positions, typically spending the fall term at Berkeley and the spring semester at Caltech. At both schools he attracted outstanding students who helped to bring American physics into the ranks of the world's best.

One of the most heated controversies of the early 1930s was over a theory proposed by Dirac. On January 2, 1928, the editor of the Proceedings of the Royal Society received a manuscript from Dirac entitled "The Quantum Theory of the Electron." This paper, along with a second part published a month later, was probably Dirac's most significant accomplishment. The relativistic wave equation he devised to describe the electron thrilled physicists in that it yielded the particle's spin and correct magnetic moment. Yet this paper also raised vexing issues. Heisenberg wrote to Pauli in July 1928 that the "saddest chapter of modern physics is and remains the Dirac theory." The principal problem with Dirac's wave equation was that it gave solutions corresponding both to positive energy states and to an infinite number of negative energy states. In such a situation, quantum mechanics predicts that electrons can jump into these negative energy states, and so all electrons could end up there. Accordingly, ordinary electrons should not exist.

To avoid this difficulty, Dirac imagined that these negative energy states were occupied by an infinite number of electrons. If a few of these states were unoccupied, however, they would appear as positive holes in the negative sea of charge. In March 1930 Dirac published a paper asserting that these positive holes were protons. But Oppenheimer, who read Dirac's paper before publication, argued in a letter to Physical Review, printed the same month, that they were not. He pointed out that if the positive holes in Dirac's theory were protons, then electrons and protons would annihilate one another, meaning that ordinary matter would have a lifetime of approximately 10^{-10} second. He further made note that the positive particles posited by Dirac's theory needed to have the same mass as an electron. In fact, these positive holes were positrons, the electron's antiparticle, but in 1930 this particle was unknown and unanticipated. In contesting Dirac, though, Oppenheimer fell just short of predicting its existence.

Even after the Caltech physicist Carl Anderson's discovery of the positron in 1932, positron theory resulting from Dirac's work was plagued with problems. Oppenheimer and other physicists working on quantum electrodynamics (QED) had many doubts about the basic theory. In 1930, for example, Oppenheimer showed that when the QED theory published that same year by Heisenberg and Pauli was applied to the interactions between electrons, protons and an electromagnetic field, the displacement of spectral lines was infinite. Oppenheimer's skepticism about QED was kept alive throughout the 1930s by anomalies in his cosmic-ray work caused by the muon and other high-energy particles unknown at the time. Had Oppenheimer had an experimental result on the hydrogen atom obtained by his student Willis E. Lamb only after the war, it is conceivable that he would have resolved the troubling problem of infinities.

In 1931 Oppenheimer attempted to find an equation for the photon that would be an analogue to Dirac's equation for the electron. He failed in this effort but in the process demonstrated the basic di›erence between particles of half-integral and integral spins, which later constituted the basis for Pauli's formal proof of the connection between spin and statistics. According to quantum mechanics, both the annihilation and the creation of matter—subject to the conservation laws of energy and momentum—are possible. A gamma ray, for example, can give rise to an electron and a positron in a process called pair production. Oddly, Oppenheimer did not originate the idea of pair production, but along with his student Milton S. Plesset, he did provide the first correct description of it in 1933. Working with his postdoctoral student Wendell H. Furry a year later, Oppenheimer developed electron-positron theory essentially in its modern form. They showed that the observed charge of the electron is not the true charge and, in doing so, anticipated the phenomenon called charge renormalization, which helped to explain some of the earlier difficulties surrounding infinities in QED.

Creation and Destruction of Matter

In the 1930s most of the high-energy physics experimentation was happening in the earth's atmosphere. There energetic particles (in the billion-electron-volt range) having cosmic origins bombarded atmospheric atoms. It was during a cloud-chamber study of such cosmic radiation in 1932 that Anderson first discovered the positron. If a metal plate of, say, lead is placed in a cloud chamber, a single cosmic-ray track incident on the plate from above the surface can give rise to a number of tracks emanating from a point on the plate's lower surface. Oppenheimer and his student J. Franklin Carlson showed that these cosmic-ray "showers," commonly consisting of photons, electrons and positrons, are produced by a cascade of electron-positron pair productions. The thickness of the lead plate can, of course, be varied. If the primary cosmic ray was either a photon or an electron, Oppenheimer and Carlson noted that a lead plate 20 centimeters thick absorbed all the resulting radiation for the energy ranges experimentally observed.

Additional data revealed, however, that penetration exceeded depths that could be attributed to either photons or electrons. They concluded that "there is another cosmic-ray component." A few months later groups at Caltech and at Harvard simultaneously discovered a new particle. Oppenheimer and his Berkeley colleague Robert Serber immediately equated this particle with one the Japanese physicist Hideki Yukawa had predicted to explain nuclear forces. The newly discovered particle in fact turned out to be the muon. The pion—Yukawa's prediction—came later.

Away from Caltech at Berkeley, Oppenheimer's research revolved around the accelerator. When James Chadwick discovered the neutron in 1932, the proton-electron theory of the nucleus was abandoned, and the modern proton-neutron model took its place. During the spring of 1933 Lawrence first began accelerating deuterons, consisting of a single neutron and proton, and using them to bombard heavy nuclei. Deuterons, he found, disintegrated nuclei more effectively than did protons. In no time at all, Lawrence and his coworkers observed alpha particles coming out of target nuclei.

Then they came on a puzzling result: when high-energy deuterons hit any nucleus whatsoever, the target would give off protons within a narrow energy range. In fact, deuterons contaminating Lawrence's apparatus accounted for the mystery: the protons he witnessed all resulted from deuterium fusion. But before this explanation emerged, the observation stimulated questions about deuterium-induced reactions. At Berkeley, Oppenheimer and his student Melba N. Phillips showed that when a deuteron collides with a heavy nucleus, that nucleus can capture the neutron in the deuteron, liberating the proton. The theory Oppenheimer and Phillips formulated for this reaction, now named after them, accounted exactly for Lawrence's strange results.

Now accepted as end points in stellar evolution, neutron stars and black holes were both postulated on theoretical grounds during the 1930s. Oppenheimer and two of his students, George M. Volkoff and Hartland S. Snyder, were in the vanguard of this development. Oppenheimer and Volkoff together became interested in another worker's suggestion that once a sufficiently massive star had exhausted its source of thermonuclear energy, a neutron core could be formed. To test whether this scenario was possible, Oppenheimer and Volkoff set out to establish the difference between a gravitational treatment of the process, based on Newton's theory, and one consistent with Einstein's general relativity.

Neutron Stars and Black Holes

The Oppenheimer-Volkoff equation, which gives the pressure gradient within the star, revealed that the pressure increased more rapidly moving deeper into the stellar core than would be expected from a Newton-based calculation. Thus, the Oppenheimer-Volkoff theory, based on general relativity, predicted stronger, and more accurate, gravitational forces than did Newtonian theory. Oppenheimer and Volkoff also performed the first detailed calculations establishing the structure of a neutron star, thereby laying the foundation for the general relativistic theory of stellar structure. Just before Oppenheimer and Volkoff published a paper on this work in 1939, Oppenheimer sent a letter to George E. Uhlenbeck, a theoretical physicist at the University of Michigan, who, with his colleague Samuel A. Goudsmit, discovered the electron's spin. He wrote, "We have been . . . working on static and nonstatic solutions for very heavy masses . . . old stars perhaps which collapse to neutron cores. The results have been very odd. . . ."

The results in fact became even stranger. Later that year Oppenheimer and Snyder published a classic paper entitled "On Continued Gravitational Contraction." They noted that when a massive star has exhausted its internal source of nuclear energy, its ultimate fate is determined by how much mass it can shed, either through radiative expulsion or by rapid rotation and flying apart. After all avenues for ejecting mass have been traversed, the core that remains is bound together by the gravitational force. If there is no thermonuclear energy to act as an equilibrating counterforce, the core will continue to collapse. As this collapse takes place, the light radiating from the core becomes increasingly redshifted, meaning its wavelength lengthens; further, the path along which this light can escape into space becomes increasingly narrow until the path closes on itself, leaving behind a source of gravitational attraction shut off from external observation. In constructing this description, Oppenheimer and Snyder provided the first calculation revealing how a black hole can form. In May 1994 compelling evidence was observed through the eye of the Hubble Space Telescope for the presence of a massive black hole in the center of the galaxy M87, the biggest and brightest in the Virgo cluster. Oppenheimer's contribution to physics throughout the century was broad, deep and lasting. The Born-Oppenheimer approximation, the penetration of electrons through potential barriers, the theory of cosmic-ray showers, neutron stars and black holes are all a vital part of contemporary physics.

Pulsars, now recognized as spinning neutron stars, were first seen in 1967, the year Oppenheimer died of cancer in Princeton. Had he lived longer, Oppenheimer might have enjoyed the recognition this discovery brought to his prewar physics, something that had been overshadowed by his wartime work and postwar fame.

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Further Reading

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