MERLE ANTONY TUVE: PIONEER NUCLEAR PHYSICIST

Working during the years between the world wars, first with Tesla coils and then with Van de Graaff generators, he established one of the earliest nuclear physics programs based on particle accelerators.

Thomas D. Cornell

Despite the effects of the Depression on the institutions that supported its work, the American physics community of the 1930s was booming intellectually. In particular, many of its members were contributing significantly to the rapid emergence of nuclear physics as a distinctive field of research. Among the most active of these participants was Merle Antony Tuve.

Perhaps the most convenient way of introducing Tuve is to say that his experiences closely paralleled those of his friend, Ernest O. Lawrence, who invented the cyclotron in 1929. Both were born in Canton, South Dakota, in 1901—Lawrence in August, and Tuve in June. Both were the sons of educators and the grandsons of Norwegian immigrants. Both "monkeyed wireless" as teenagers, studied physics in college and developed particle accelerators during the years between the world wars. After World War II began, both assumed important responsibilities—Lawrence with the atomic bomb project, and Tuve with the group that developed the proximity fuse. Finally, during the postwar era both led important research organizations—Lawrence at the Radiation Laboratory of the University of California at Berkeley, and Tuve at the Department of Terrestrial Magnetism, a research agency of the Carnegie Institution of Washington.

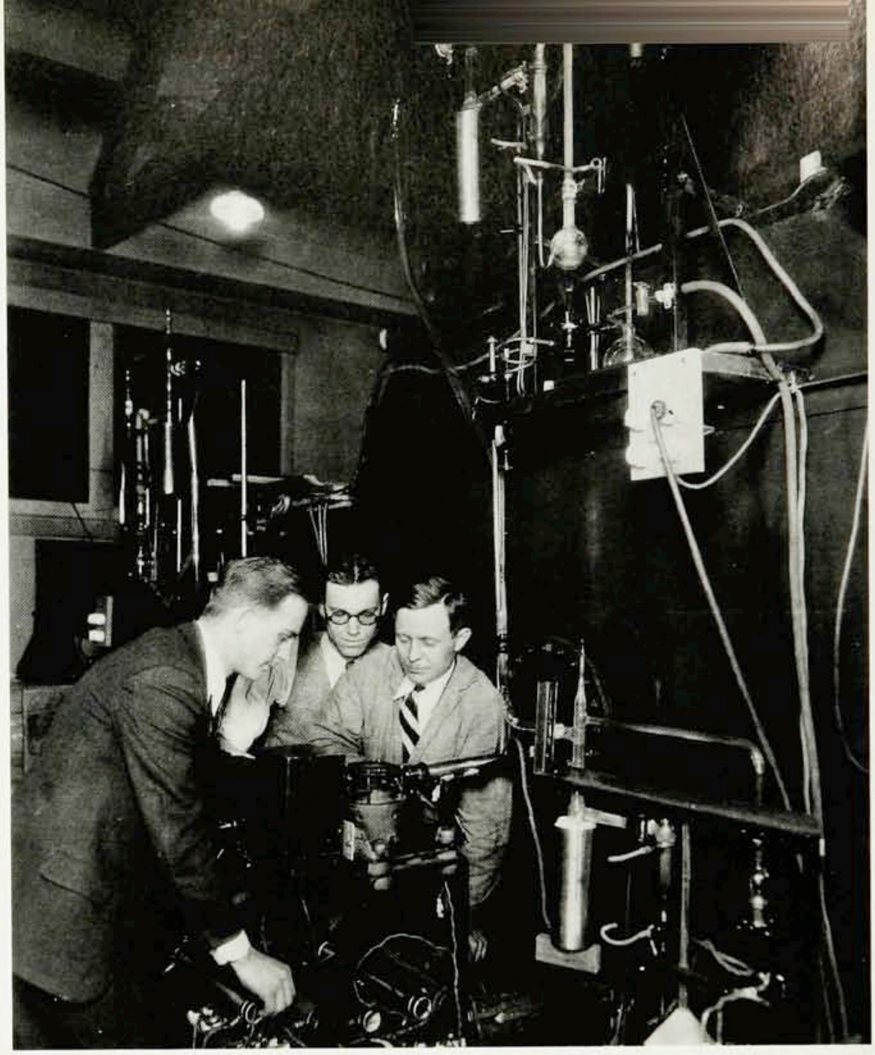
Of course, they had their differences as well. For example, they held different attitudes toward the publication of their experimental results. Tuve viewed research as the means of establishing scholarly benchmarks and preferred to delay publication until he had checked his results thoroughly. Accordingly, the author of a popular article in the 1930s described him as "extremely careful of the scientific accuracy of his work and conservative in statements about it."[1] Lawrence, by contrast, favored prompt publication. "He's a brash young man," Ernest Rutherford once said of him, "but he'll learn!" (See M. L. E. Oliphant's article in PHYSICS TODAY, September 1966, page 46.)

Despite such differences, however, Tuve and Lawrence played similar roles in changing the way in which physics is done. As graduate students, both learned the old style of laboratory work in which the experimentalist was something of a master craftsman, skilled in building small-scale equipment and adroit in using it to address important intellectual questions. But in the course of establishing their nuclear physics programs both began acting as engineers and administrators, becoming versed in erecting large, complex facilities and effective in directing the researchers who used them. Thus both helped to create the technology-intensive, team-oriented approach to experimental physics that has emerged as one of the most distinctive features of science in the 20th century.

Becoming a physicist

Tuve developed a serious interest in physics during his undergraduate years at the University of Minnesota. Although he intended to major in chemistry when he went

Thomas D. Cornell is assistant professor of the history of science at the Rochester Institute of Technology.



Merle A. Tuve, Lawrence R. Hafstad and Odd Dahl examine the target assembly of their most powerful Tesla apparatus, consisting of a Tesla coil and a high-voltage tube mounted in a tank of oil under pressure, in January 1931.

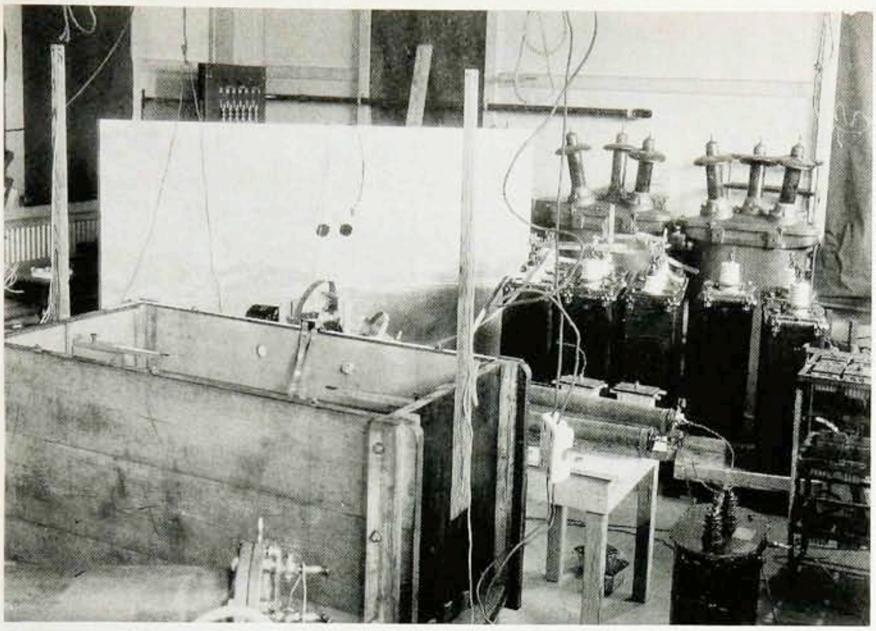
to Minneapolis for the start of the spring quarter in 1919, he soon switched to electrical engineering. Among the requirements for his new major was an introductory physics sequence. That—plus John T. Tate's theoretical physics sequence (which Tuve began during the fall of 1921)—clinched his interest. Accordingly, by the time he received his baccalaureate in electrical engineering in mid-1922 he had decided to work on a master's degree in physics.

During the summer of 1922, Tuve considered what he would do for his graduate research project. Initially, he planned to use vacuum tubes to produce electromagnetic waves with wavelengths less than a meter, which then marked the edge of the wavelength frontier. Such work also appealed to Lawrence, who had become interested in physics as a student at the University of South Dakota, and who planned to join Tuve at Minnesota. "A duplex team in research would be great," Lawrence wrote his friend. "Some phase of the vacuum tube seems to offer infinite possibilities to me."[2] Nevertheless, each ended up pursuing a different project. Under Tate's direction Tuve studied the ionization of mercury atoms bombarded by mercury ions, while Lawrence, under the direction of W. F. G. Swann, studied the electrical effects produced when metallic spheroids are rotated in magnetic fields.

In 1923 Tuve received his master's degree and accepted an instructorship at Princeton, where he hoped to continue his positive-ion studies (under the supervision of Karl T. Compton) as the basis for his doctorate. But after the department failed to renew his instructorship for the following year, he arranged to go to The Johns Hopkins University. During the summer of 1925 he worked with Gregory Breit, a theoretical physicist at the Carnegie Institution's Department of Terrestrial Magnetism whom he had met at Minnesota. Assisted by the staff of the Naval Research Laboratory, Tuve and Breit used radio wave pulses to demonstrate directly the existence of the conducting layer of the Earth's atmosphere. Tuve's adviser at Johns Hopkins, Joseph S. Ames, accepted the project as the basis for his doctorate, and Tuve completed his degree in 1926.

Early work with Tesla coils

As an undergraduate at Minnesota, Tuve had become familiar with Rutherford's work. Based on scattering experiments in which he used alpha particles from a radioactive source to bombard metallic foils, Rutherford had proposed the nuclear model of atomic structure in 1911. Tuve was intrigued by the idea that electrical forces could not account for the stability of atomic nuclei, and he initially intended to study the attractive nuclear force by performing scattering experiments using beams of very-



Early version of the Tesla apparatus at the Carnegie Institution's Department of Terrestrial Magnetism in March 1927. By immersing the Tesla coil in a wooden tank filled with oil, Tuve and Gregory Breit succeeded in producing 3 million volts.

high-energy particles. But in the course of choosing the research project for his master's degree he decided against radioactivity studies, noting that it would be "Hard to compete with Rutherford here alone!"[3] Similarly, although he recognized that an alternative approach to scattering experiments would be to use a high-voltage source to accelerate charged particles (specifically, he had in mind a Tesla coil), he did not have access to the requisite high-voltage equipment.

In September 1924 Tuve heard Rutherford speak at a meeting of the Engineer's Club at Western Electric (New York), where Tuve was completing a summer project under the direction of Clinton J. Davisson. Later, as his graduate work at Johns Hopkins drew to a close, he even considered applying for a fellowship from the National Research Council so that he could join Rutherford at the Cavendish Laboratory in Cambridge, England. But John A. Fleming, the Department of Terrestrial Magnetism's assistant director, talked him into coming to Washington instead, by promising the young physicist that he could spend part of his time developing accelerators for a program of nuclear studies if he would spend the rest of his time continuing the radio work.

At the Department of Terrestrial Magnetism, Tuve became a member of the research group that turned the radio pulse-echo method into a powerful tool for studying the conducting layer of the Earth's atmosphere. In 1927 he and Breit were joined by Odd Dahl, and in 1928 Lawrence R. Hafstad arrived. Although Tuve became the group's leader after Breit's departure in the late 1920s, Breit remained affiliated with the group as one of the Carnegie Institution's research associates.

In addition to the radio work, the Washington group began developing the Tesla coil as a particle accelerator. In a talk at the Carnegie Institution in November 1928, Tuve explained the choice of the Tesla coil. Although companies such as General Electric were already operating high-voltage apparatus (usually cascade transformers or impulse generators) for testing purposes, their equipment was powerful, massive and expensive. "For scientific purposes," Tuve noted, "a high-voltage equipment of small power is more suitable, being less expensive and more easily handled or controlled."[4]

The question that Tuve amd Breit posed for themselves when they initiated the project in 1926 was whether or not the Tesla coil could produce upward of 5 million volts—so that the accelerated particles would have energies comparable to those of particles from radioactive sources. Only then, they believed, could one use the apparatus to repeat and extend Rutherford's work, which since 1919 had come to include disintegration experiments.

Working in the Department of Terrestrial Magnetism's Experiment Building, they found that an open-air Tesla coil could be operated only up to about 500 000 volts. To circumvent the corona discharge and sparking that limited further advances, they mounted the coil in a wooden box filled with transformer oil. As a result, they were able to reach about 3 million volts. Finally, to push the maximum even higher, the Washington group mounted the coil in a large, oil-filled metal tank. When operated under pressures of about 500 psi, the new version of the device produced 5.2 million volts.

Because existing vacuum tubes invariably failed in the region above 300 000 volts due to electron emission from the cathode, the next stage in the project was to develop suitable high-voltage tubes. In the spring of 1928, after trying several approaches without success, Tuve and his coworkers adopted a technique that William D. Coolidge had developed at General Electric. Instead of putting the entire voltage across one tube, they connected several tubes in series. Using these "cascade tubes," the group succeeded in putting 1.4 million volts across a 15-section tube by the summer of 1929.

The Van de Graaff generator

In 1930 Tuve and his coworkers published papers[5] on both the Tesla apparatus and the high-voltage tubes in *Physical Review*. But even though the physics community had long accepted instrument development as a legitimate aspect of physics research, Tuve had not undertaken such work as an end in itself. From the beginning his primary aim had been to use the equipment for a program of nuclear studies. Thus in early 1930 he wrote Karl F. Herzfeld at Johns Hopkins that the project "is at present passing rather slowly through a transitional stage between the tube development work and the 'real physics,' which is just beginning."[6]

The next step toward doing "real physics" was to produce gamma rays and high-energy beams of electrons and protons. In May 1930 Tuve and his coworkers took their first photograph of a beam of accelerated electrons, or "artificial beta-rays," as Tuve called them.[7] During the summer they boosted the accelerating potential to more than a million volts, and at about the same time they produced gamma rays of comparable energy.

In December, Tuve described the group's progress at the Cleveland meeting of the American Association for the Advancement of Science. Soon afterward, he learned that the group had been awarded the society's $1000 prize for the best paper presented at the meeting. "I am awfully glad that such an extraordinarily fine recognition has come to you and your work," Lawrence wrote Tuve on hearing the news.[8] "It is a well deserved reward for carrying a difficult job to a brilliant conclusion."

Nevertheless, Tuve fretted over the problems that were preventing the group from operating the apparatus as a proton accelerator, such as obtaining a satisfactory proton source and convincing the machine-shop personnel to finish building the cloud chamber that the physicists had requested. But by far the most troubling problem was the Tesla apparatus itself. Because the voltage oscillated so rapidly and was so strongly damped, the peak was too transient for large numbers of protons to be accelerated to full speed.

By the late 1920s Tuve and his coworkers had already begun their search for a replacement technology. In 1928, they tried out Breit's idea for an electron accelerator that employed a changing magnetic field. Later in the year, when Lawrence came through Washington on his way to Berkeley, Tuve encouraged him to try his hand at building accelerators. During the summer of 1930 Hafstad examined some of the equipment being used in Europe—visiting, for example, the Berlin laboratory of Arno Brasch and Fritz Lange to find out more about their impulse generators. Meanwhile, back in the United States, Tuve not only contacted the Kelley–Koett Company of Covington, Kentucky, regarding cascade transformers but also proposed his own design for an impulse generator.

It turned out to be the Van de Graaff generator that enabled the Department of Terrestrial Magnetism researchers to forge ahead. Since the fall of 1929, Robert J. Van de Graaff had been building prototypes of his invention at Princeton as a National Research Council Fellow. After learning about the project through mutual Princeton friends, Tuve became excited by the prospects of an open-air version (Van de Graaff had been concentrating on versions mounted in vacuum tanks) that could produce a million volts, and he encouraged Van de Graaff to proceed with the initial tests as quickly as possible.

In August 1931 Tuve learned that Van de Graaff had produced 1.5 million volts using silk belts to deposit electrical charge on a pair of metal spheres, each 2 feet in diameter and resting on a 7-foot Pyrex rod. Tuve then arranged to bring him and his equipment to Washington to try it out with the department's high-voltage tubes. The success of these tests led Tuve to conclude: "This simple device . . . will undoubtedly alter the whole course of high-potential experiments, here and elsewhere."[9]

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Robert J. Van de Graaff at Princeton in September 1931. After successfully operating his apparatus, Van de Graaff loaded it on Tuve's car and traveled to Washington for tests using the Department of Terrestrial Magnetism's high-voltage tubes.

As 1931 gave way to 1932, the Washington group came under even greater pressure to switch to the new device. Although they had acquired a second (and larger) tank for the Tesla coil and had finally succeeded in using the apparatus to produce a beam of accelerated protons, their slow rate of progress contrasted strikingly with the rapid sequence of events in nuclear physics—Harold C. Urey's discovery of heavy hydrogen, James Chadwick's discovery of the neutron, and John D. Cockcroft and Ernest T. S. Walton's use of a particle accelerator to disintegrate lithium.

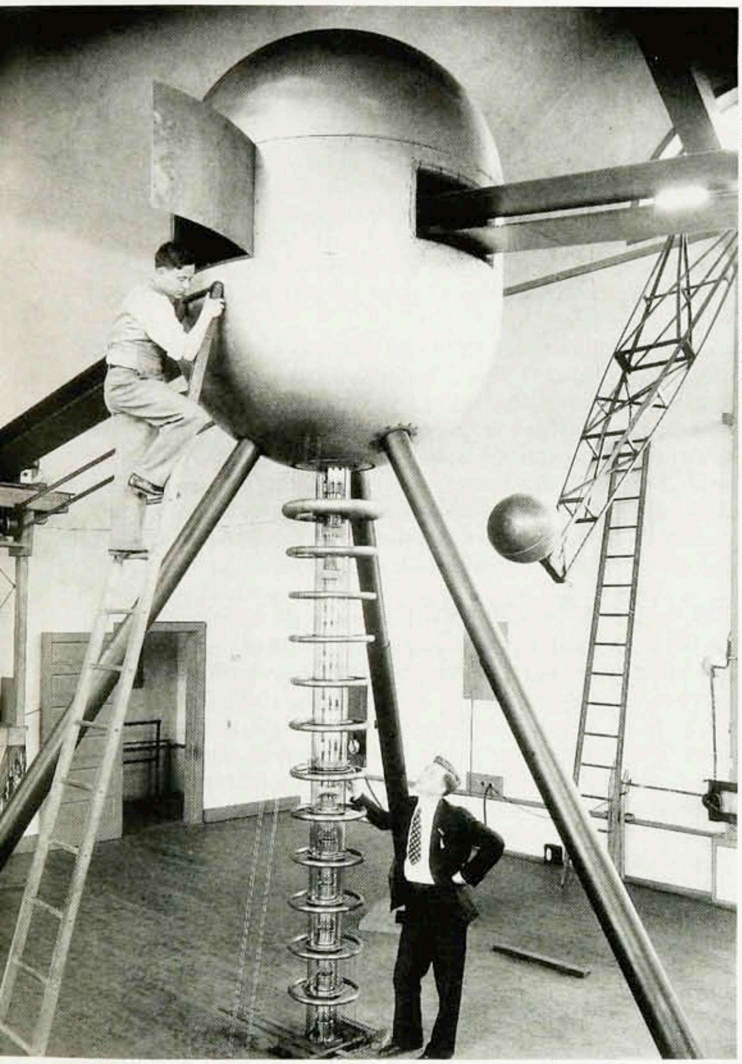
Tuve's response to these events was to strengthen the technical basis for his proposed program of nuclear studies. In May 1932 he and his coworkers erected on the lawn behind the Experiment Building a Van de Graaff generator that used an aluminum sphere 2 meters in diameter. Their tests quickly showed not only that the device was capable of producing at least 2 million volts, but also that the tubes could withstand close to 1 million volts.

Knowing that he could proceed no further without official support, Tuve requested the additional funds needed to house the 2-meter machine. He also sought permission to remove the Tesla tanks to allow for the construction of a 1-meter machine inside the Experiment Building. But Fleming, who was by then the department's acting director, would not approve these requests without first consulting Carnegie Institution president John C. Merriam (and others) about the wisdom of expanding the high-voltage work. Official approval was not forthcoming until October 1932—after a two-day conference to consider Tuve's plans.

Subsequently, Tuve and his coworkers lost no time in ripping out the Tesla tanks and installing the 1-meter machine, which was operational by the end of the year. But the effects of the Depression on the Carnegie Institution prevented funds for housing the 2-meter machine from being appropriated until early 1933. Moreover, Tuve soon discovered that the increased scale of the project was itself a source of delays.

Controversial results

When they finally began their experimental program, Tuve and his coworkers took their bearings from the Cavendish Laboratory. Due to the theoretical work of George Gamow and others, the announcement by researchers at the Cavendish Lab that protons accelerated through less than 600 000 volts could split lithium nuclei came as no surprise to many physicists. But the disintegrations they reported for heavier elements were harder to accept. Thus in early 1933 Breit advised[10] his Washington colleagues: "Am not sure that it is wise to be leaving heavy elements alone." "If [Cockcroft and Walton] are right about the heavy elements," he pointed out, "the ordinary disintegration theory needs considerable revision." And if the existing theory was indeed correct, there remained the problem of explaining the Cambridge results.



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Tuve and Dahl (on ladder) examine the Department of Terrestrial Magnetism's 2-meter Van de Graaff generator in May 1935. The cylindrical section separating the two (2-meter) hemispheres provided room for the belts that delivered charge to the generator and for the ion source. After sufficient positive charge had been built up on the machine's outer surface, the ions were accelerated through the vertical tube (against which Tuve is leaning) to the target chamber in the laboratory below.

In mid-1933, Tuve and his coworkers reported that they had used 600 000-volt protons from the 1-meter machine to bombard aluminum, nickel and silver.[11] (Later work demonstrated that the useful maximum for the 1-meter machine was closer to 400 000 volts.) In each case, they observed many fewer disintegrations than had the Cambridge researchers. Moreover, they found that the energies of the disintegration products corresponded quite closely to those observed in large amounts from targets of boron, which Tuve considered a likely contaminant because of the widespread use of borax soap.

Uncovering contamination effects also proved to be the main theme for the earliest work with the 2-meter machine. This time, however, the Washington researchers took their bearings from Lawrence's laboratory at Berkeley. When Tuve's new machine finally became operational in late 1933, producing more than 1.2 million volts, Lawrence's cyclotron was the only other accelerator capable of producing particles in the same voltage range. Earlier, the Berkeley group had used ions of heavy hydrogen, which they called[12] "deutons," to bombard a wide variety of substances. To account for some of their observations, they had hypothesized that the deuterons (as they are now called) were less stable than expected and were breaking up in the vicinity of the target nuclei.

In February 1934 Tuve informed Lawrence that he and his coworkers were having difficulty verifying the Berkeley results. A subsequent series of experiments reinforced Tuve's suspicion that something was amiss at his friend's laboratory. After replacing their solid targets with gaseous targets of high purity, the Washington researchers observed that deuteron bombardment produced no disintegrations. But whenever they introduced small amounts of deuterium gas (supplied by Urey) into a target, numerous disintegrations resulted. Accordingly, Tuve concluded that what the Berkeley researchers had observed was actually the result of deuterons colliding with deuterons.

By then, however, Lawrence had publicly withdrawn his support for the hypothesis of deuteron instability, and in his private correspondence he made it clear that he intended to exercise greater care in the future. Similarly, Cockcroft[13] remarked in a letter to Tuve: "We had our first lesson in the impurity effect for protons on heavy elements; Lawrence has now had his, and [Brasch and Lange] have so far been wrong as often as right. . . . There is a real danger of the subject getting into a mess, and I feel that the only thing to do is to delay publication until we are reasonably sure."

Of course, Tuve agreed. Nevertheless, in the confusion caused by the complex new equipment they were using and by the puzzling natural phenomena they were investigating, he and his coworkers made mistakes. Their errors involved artificial radioactivity, which Frédéric Joliot and Irène Curie had discovered earlier in the year. Specificially, Tuve and Hafstad stated in print that if protons caused artificial radioactivity in carbon, the effect was slight—and that the positive results reported by other laboratories were probably due to contaminants.[14] However, after discussions in June 1934 with Lawrence in Berkeley and with Charles C. Lauritsen at Caltech, Tuve came to the painful conclusion that the effect in carbon was real after all. Thus he confided[15] to Hafstad: "Am nearing the end of a hell of an uncomfortable trip. Nuclear physics isn't physics yet, and symposiums on a subject that isn't born yet are premature .... I'll go into the details when I reach [Washington], but this is just a tardy warning that we haven't got the world by the tail yet."

A center for nuclear physics

Despite Tuve's distress over his error, the technical basis had indeed been laid for systematic experimental work in the new field. But successful accelerator development was not the only reason for the emergence of the Department of Terrestrial Magnetism as a leading center for nuclear physics. Also important was the improvement of the group's contacts with theoretical physicists. During the summer of 1934 Tuve helped to secure Gamow's appointment at nearby George Washington University, and a year later the university hired Edward Teller as well. Moreover, in the spring of 1935 the Carnegie Institution and George Washington University sponsored a three-day conference that allowed a small group of theorists to discuss contemporary problems in nuclear physics. Similar conferences on other topics in physics became annual events in Washington.

Finally, there was the successful pursuit of the experimental program using the 2-meter machine. For example, in early 1935 Tuve and his coworkers demonstrated that carbon, lithium and fluorine showed resonance effects under proton bombardment. At certain specific energies, which differed from target to target, the accelerated protons were much more effective at causing nuclear reactions than at other energies.

When the summer humidity (which caused sparking along the belts or short-circuited the generator along the outer surface of the vacuum tubes) put a temporary end to these experiments, Tuve and his coworkers, assisted by Raymond G. Herb from the University of Wisconsin, constructed a high-resistance voltmeter so that they could measure the accelerating potential more precisely. With the arrival of drier weather in the fall, the group—which by then included Norman P. Heydenburg—began studying how protons are scattered by protons. During 1936 the group obtained results that enabled Breit and two other theorists to conclude that the forces at work in the proton–proton interaction are the same as the forces at work in the neutron–proton interaction.[16] Thus the group's experiments contributed directly to a better understanding of the strong force.

In the spring of 1936 the group began another important line of research. Assisted by Lynn H. Rumbaugh from the Bartol Research Foundation, the group examined the effects of proton and deuteron bombardment of different lithium isotopes. During the summer of that year the group collaborated with Edoardo Amaldi, a member of Enrico Fermi's group in Rome, to study the neutrons produced when various targets were bombarded with deuterons.

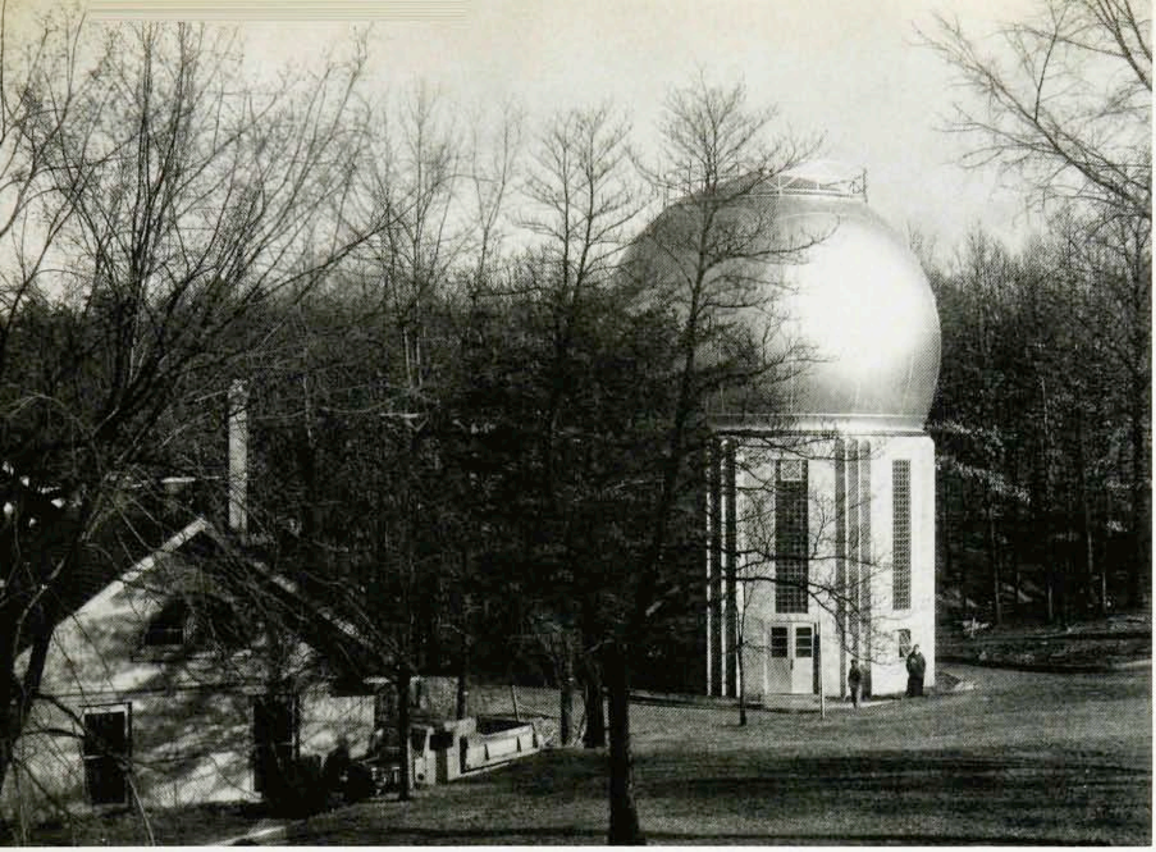
Other physicists responded favorably to the published descriptions of both the 2-meter machine and the various experimental results.[17] For example, Rutherford congratulated the Washington researchers on their studies of the lithium isotope reactions and the scattering of protons by protons. "I am very pleased," he added, "to see that the rush period of work on transmutation has come to an end, and as your papers show, results of real value can only be obtained by accurate and long continued experiment."[18]

Expanding the program

As the department program matured, one of its characteristic features became the simultaneous pursuit, on an increasingly grand scale, of experimental physics and instrument development. Thus after visiting the Cavendish Laboratory in October 1934, Hafstad reported that their own efforts in the million-volt range had forced them to deal with problems that the British group had not yet faced. "With this in mind," he continued, "our contributions to nuclear physics should properly be compared only to those of the Berkeley investigators, who are at present the only other group pioneering in both the method of attack and in the analysis of reactions."[19]

By then Tuve had decided that the Department of Terrestrial Magnetism should build a more powerful accelerator. Initially, the limitations of open-air Van de Graaff generators led him to explore the possibility of an entirely different method—one that Jesse W. Beams and Leland B. Snoddy were developing at the University of Virginia. But in early 1935 he realized that it would be feasible to build a larger Van de Graaff generator if it was placed in a controlled atmosphere under pressure. On a smaller scale, that idea was already the basis for the work of Herb's group at the University of Wisconsin. What attracted Tuve, however, was the prospect of mounting a huge generator inside a spherical tank like those coming into use for industrial storage purposes.

In September 1935 Tuve formally proposed the



Pressurized Van de Graaff generator at the Department of Terrestrial Magnetism in December 1937. The Experiment Building is to the left. The construction of the new facility continued the department's dual commitment to experimental physics and instrument development.

construction of "A Full-Scale Equipment for Researches in High-Energy Physics."[20] Although the new apparatus would be expensive ($150 000 according to Tuve's estimate), he argued that the Department of Terrestrial Magnetism was better prepared than most universities to undertake a project of such "colossal technical scope." Moreover, he believed that the proposed facility would "meet the needs of a whole generation of investigators" in much the same way that the Yerkes and Mount Wilson telescopes were serving astronomers, and would thereby enable his group to maintain its leadership in a field that constituted "perhaps the most important modern aspect of natural philosophy."

Again, however, the official decision to proceed was slow in coming. Not until the spring of 1936, when Tuve decreased the scale of his project, from a 60-foot sphere to one 30 feet in diameter (thereby decreasing the estimated cost to $23 650), did he receive approval. Moreover, because of the Department of Terrestrial Magnetism's residential setting, no building permit was issued until early 1937, when the zoning commission of the District of Columbia received assurances that the structure would have a suitably pleasing design.

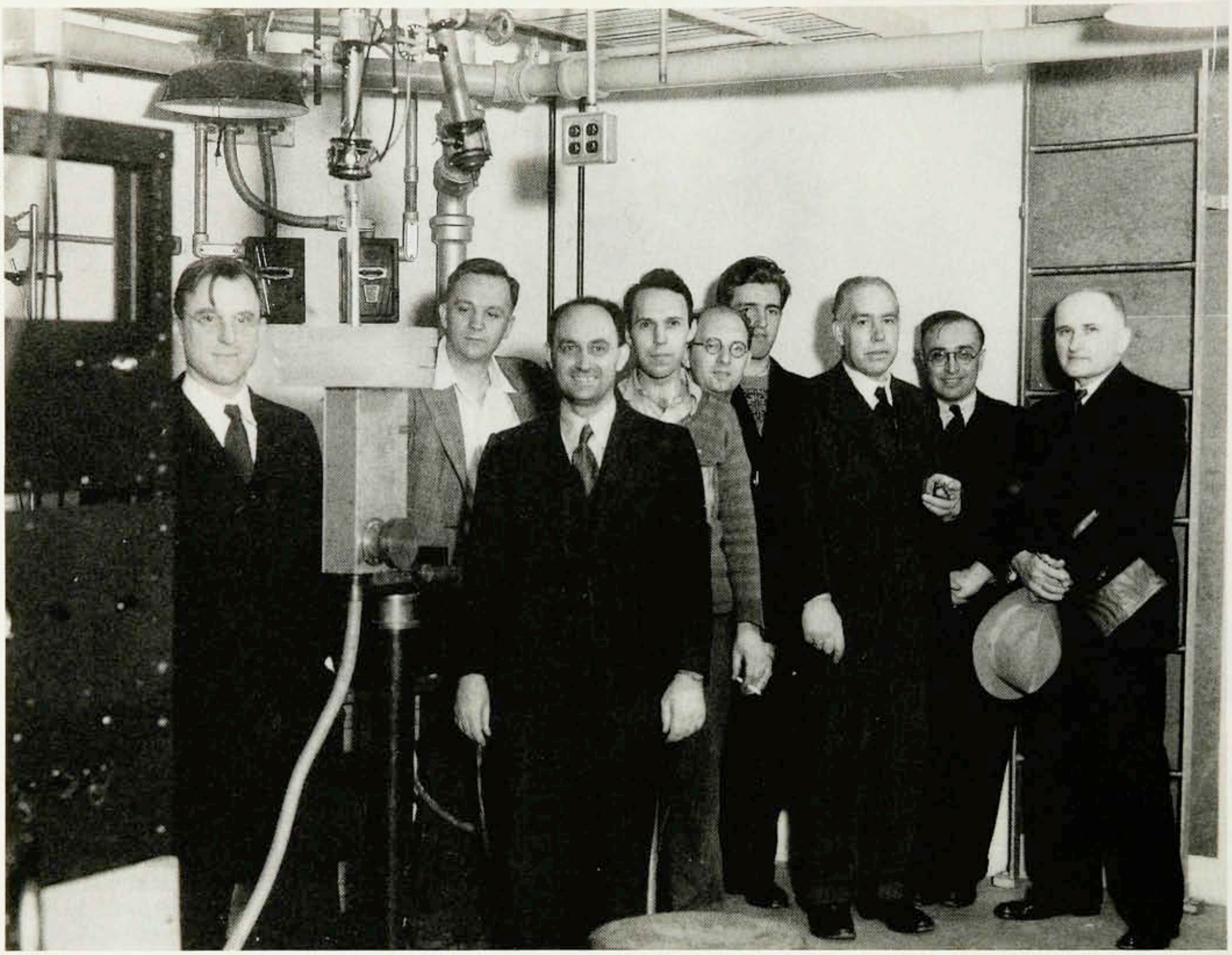
After that, however, progress was steady. By fall the Chicago Bridge and Iron Works had completed the pear-shaped pressure vessel, and by year's end its lower portion had been sheathed in brick. Then the work began on the generator itself. In May 1938 the massive steel cap was placed securely on four insulating columns, topping off what Tuve described to James Franck as "our mountain of steel and porcelain."[21] At year's end, the Atomic Physics Observatory was operational, with useful accelerating potentials that reached nearly 3 million volts.

Meanwhile, the size of the group was increasing. In 1937 the Department of Terrestrial Magnetism established a program of research fellowships, the first of which went to Richard B. Roberts. At the beginning of 1939, after Vannevar Bush had replaced Merriam as president of the Carnegie Institution, the department undertook the construction of a 60-inch cyclotron, which brought still more physicists into the group. The group also expanded the hours that the 2-meter machine was in use, prompting Tuve to note in one of his monthly reports that "it has become customary to operate the high-voltage equipment during the day on proton scattering and most of the night on the lithium observations."[22]

Throughout this same period, the Washington conferences kept Tuve and his coworkers abreast of the latest theoretical developments. In 1938, for example, physicists and astrophysicists discussed ways in which the new knowledge of nuclear reactions could be applied to the question of how the stars produce their energy. The meeting proved especially fruitful for Hans A. Bethe, who proposed the carbon cycle not long after participating.

Officially the topic of the 1939 conference was low-temperature physics. But Niels Bohr brought with him the astonishing news that researchers in Germany had recently discovered a new type of nuclear reaction. Tuve immediately arranged for the department to verify the occurrence of uranium fission, and by the final day of the meeting the Atomic Physics Observatory was ready. "That evening," recalled writer Robert D. Potter, "Bohr and Fermi, with other invited guests, saw the experiments for the first time with their own eyes."[23]

Although the Washington group continued to study the fission reaction, Tuve remained cautious in assessing its practical applications. He agreed to serve as a member of the Uranium Committee that President Roosevelt authorized in the latter part of 1939. But by mid-1940 he felt the need to make more immediate contributions to the nation's military preparedness. In particular, he became head of "Section T" of the National Defense Research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Verification of uranium fission at the Department of Terrestrial Magnetism on 28 January 1939 was witnessed by (left to right) Robert C. Meyer, Tuve, Enrico Fermi, Richard B. Roberts, Leon Rosenfeld, Erik Bohr, Niels Bohr, Breit and John A. Fleming.

Committee and turned his attention to developing the proximity fuse.

His break with nuclear physics turned out to be permanent. Although the Department of Terrestrial Magnetism—with Tuve as its new director—continued its program of nuclear studies after the war, Tuve himself did not actively participate. Instead, his own efforts centered on explosion seismology (using conventional explosives to study the Earth's crust) and on radioastronomy.

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