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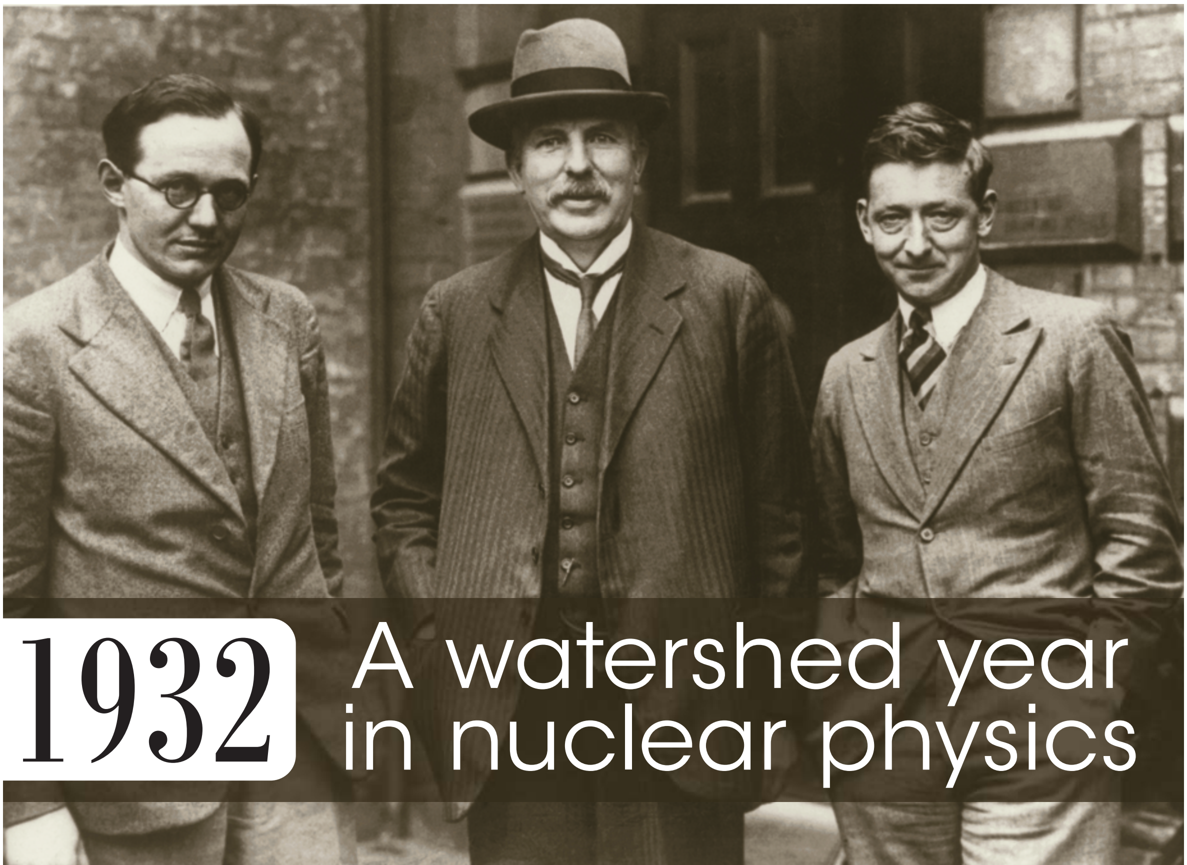

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1932 A watershed year in nuclear physics

Joseph Reader and Charles W. Clark

The consequences, for good and ill, of that annus mirabilis of discovery and invention are still very much with us.

The year was 1932, in the brief interim between two world wars. The Great Depression was near its nadir. In the US, unemployment was approaching 25%. Charles Lindbergh's baby was kidnapped and murdered, and Amelia Earhart became the first woman to fly solo across the Atlantic. Iraq was established as an independent country, and Franklin Roosevelt won the first of his four presidential elections. The American Institute of Physics was formally incorporated, and it appointed Harold Urey as the founding editor of its first journal, the *Journal of Chemical Physics*.

Urey was a 39-year-old associate professor of chemistry at Columbia University in 1932. He got off to a quick start that year: On New Year's Day, *Physical Review* published "A hydrogen isotope of mass 2," a letter to the editor by Urey, Ferdinand Brickwedde, and George Murphy that reported the discovery of deuterium.[1] That was the first of four monumental discoveries of 1932. The discoveries of the neutron,[2] the positron,[3] and the disintegration of nuclei by particle accelerators[4] followed in quick succession. Those discoveries promptly transformed the understanding of nuclear structure and demonstrated the reality of antimatter.

Six Nobel Prizes are directly traceable to the work done in that one annus mirabilis. In this article, we look back from today's perspective at those discoveries and their consequences.

Nuclear physics before 1932

In 1911 Ernest Rutherford discovered that atoms have a small, massive kernel, which he termed "nucleus," a diminutive of *nux*, the Latin word for nut. But by 1932, no one had developed an accurate concept of its constituents. In 1918 Rutherford bombarded nitrogen atoms with alpha particles (helium nuclei), thus converting nitrogen to oxygen plus a liberated hydrogen nucleus. He considered the liberated hydrogen nucleus a new particle and named it the proton. It was, he conjectured, the building block of all nuclei and accounted for their positive charges.

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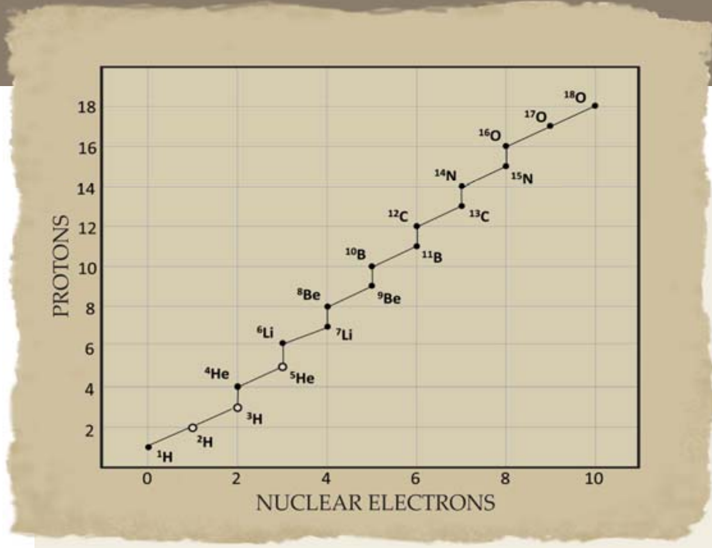


Figure 1. A re-creation of the 1931 chart of light-element isotopes that inspired Harold Urey to search for deuterium. Filled circles represent isotopes already known. Open circles represent isotopes Urey expected to find. The antiquated axes and their erroneous labels reflect the fact that the neutron had not yet been discovered. The nucleus was presumed to consist entirely of protons, which determined its mass number, and enough "nuclear electrons" to correct its net charge. Thus the vertical axis really gives mass number *A*, and the horizontal axis gives *A minus* atomic number *Z*, which is the number of neutrons.

The existence of isotopes presented a great puzzle. Isotopes had been discovered in 1912 by Frederick Soddy in his study of the decay of uranium to radon. Soddy realized that there could be versions of an element whose atomic masses differed, even though their chemical properties were the same.

The following year, J. J. Thomson succeeded in separating neon isotopes by passing a beam of neon atoms through a magnetic field. In 1920 Rutherford proposed that the difference between the atomic number of a nucleus and its atomic mass might be due to neutral particles in the nucleus. The neutral particle, he suggested, might be a combination of a proton with a "nuclear electron." But after the 1927 publication of Werner Heisenberg's uncertainty principle, the confinement of the putative nuclear electrons in a volume 10^{14} times smaller than that of an atom became a problem. Such confinement of a particle with the electron's tiny mass would impose an implausibly large kinetic energy on any nuclear electron.

Enter 1932, the year in which those problems were set on the path to resolution. Six weeks after the discovery of deuterium, James Chadwick announced his discovery of the neutron, and in August Carl Anderson announced the discovery of a positive electron—the positron. The work of incorporating the new discoveries into the emerging science of nuclear physics proceeded at a breathtaking pace (see the article by Charles Weiner in PHYSICS TODAY, May 1972, page 40).

Heavy hydrogen

Just 21 years after its discovery, deuterium fueled the first nuclear-fusion bomb. Today it lies at the heart of the hope for cheap electric power through peaceful application of the fusion process. And in modern cosmology, the measurement of the primordial deuterium abundance provides a sensitive test of Big Bang nucleosynthesis (see PHYSICS TODAY, January 2012, page 11).

Chemists had noticed that the atomic weight of hydrogen, as measured by chemical methods, differed slightly from that measured by mass spectrometry. It was thought that the discrepancy might be due to the existence of a heavy isotope of hydrogen that would be present in ordinary water at a few parts in 10^4. But searches for the putative isotope with mass spectrometers were unsuccessful. Signals in the mass-2 channel were contaminated by the presence of the molecule H_2^+, which swamped possible signals from an isotope of the same mass. Urey was convinced of the likely existence of a heavy hydrogen isotope, and he drew constant inspiration from a chart that he had made of the known isotopes and posted on his office wall. A re-creation of that chart is shown in figure 1.

In 1931, Urey had an ingenious idea for a new search technique, involving atomic spectroscopy and the Bohr model of the atom. It's easy to calculate the dependence of the energy levels of a hydrogenic atom on the nuclear mass and thus predict its spectral properties. Urey decided to look for an emission line of atomic hydrogen at the wavelength predicted for a hydrogen isotope of mass 2. According to the Bohr model, the wavelength of the Balmer-alpha line of ^{2}H should be shifted about 0.1 nm blueward of the Balmer-alpha line of ordinary ^{1}H at 656.3 nm.

The problem was how to avoid having the isotope-shifted line swamped by the ordinary Balmer-alpha line so close by. Urey decided to make samples of hydrogen in which the heavy isotope would be enriched and then use those samples to fuel the discharge in his spectroscopic light source. Being an expert on the thermodynamic properties of molecules, Urey calculated the low-temperature vapor pressures of possible molecules ^{1}H^{1}H, ^{2}H^{1}H, and ^{3}H^{1}H (in modern notation: H_2, HD, and HT [for tritium]). He predicted vapor pressures in the ratios 1.0:0.37:0.29. Thus he concluded that it would be possible to partially separate the isotopes by preparing a sample of liquid hydrogen and allowing the light isotope to evaporate preferentially.

But where could he obtain liquid hydrogen in sufficient quantity? At the time only two sites in the US could routinely produce liquid hydrogen. One was at the University of California, Berkeley. The other was at the National Bureau of Standards (now NIST) in Washington, DC. In the autumn of 1931, Urey enlisted the help of Brickwedde, chief of the low-temperature lab at NBS. (See the article by Brickwedde in PHYSICS TODAY, September 1982, page 34.)

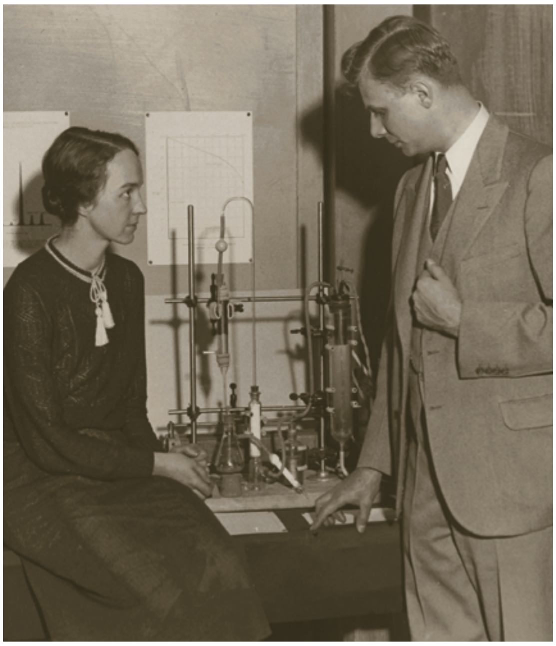


Figure 2. Ferdinand Brickwedde and his wife, Marion, at the National Bureau of Standards in the mid 1930s. Between them is the apparatus he used in the discovery of deuterium.[1]

Then only 28 years old, Brickwedde was already a star of experimental low-temperature physics. In the spring of 1931, he led an NBS team that produced the first liquid helium in the US. It may seem curious that it took so long after Heike Kamerlingh Onnes first liquefied helium in 1908 in the Netherlands (see the article by Dirk van Delft in PHYSICS TODAY, March 2008, page 36) for so important a substance to be made in the US. But the vast cryogenics infrastructure we now take for granted did not yet exist.

For Urey's project, Brickwedde produced several samples of liquid hydrogen at different degrees of distillation (see figure 2). The best sample was obtained from 4 liters of liquid hydrogen evaporated near the triple point until a residue of only 1 ml remained. The various samples were sent by Railway Express to Columbia, where Urey and Murphy investigated their emission spectra with a high-resolution spectrometer. They found that at the wavelength predicted for ^{2}H there was a line whose strength grew with the concentration of the samples. There was no sign of an isotope of mass 3. They had discovered deuterium!

Shortly after the discovery, Urey and Edward Washburn, an electrochemist at NBS, found that deuterium could be isolated relatively easily by electrolysis of ordinary water. Thus production of deuterium would not require extraordinary low-temperature efforts. Norsk Hydro's hydroelectric plant in Rjukan, Norway, soon began industrial production of "heavy water." By 1934 the plant was supplying it to customers at a cost of $500 per kilogram. Deuterium was found to have unique utility in biology, chemistry, and nuclear physics. In 1934 Urey was awarded the Nobel Prize in Chemistry "for his discovery of heavy hydrogen."

The discovery of deuterium was probably the first instance in which use of atomic theory led to the identification of a previously unknown isotope. But it shed no light on the supposed presence of electrons in the nucleus. The labeling of Urey's isotope chart implied that the deuterium nucleus consisted of two protons and one nuclear electron. The mystery of the atomic nucleus remained to be solved.

The solution was not long in coming. The very next month, Chadwick, working under Rutherford at the Cavendish Laboratory in Oxford, UK, announced the discovery of the neutron.

The neutron

As with deuterium, discovery of the neutron in 1932 brought its own burst of applications. Because the neutron is uncharged, experimenters quickly realized that it could easily penetrate nuclear Coulomb barriers. So it was promptly used to bombard many nuclear species and thus produce new isotopes.

Six years later came a momentous culmination. When Otto Hahn and Fritz Strassmann in Berlin irradiated uranium with neutrons in 1938, they found, to their amazement, that they had produced nuclei with about half of uranium's mass. They had discovered nuclear fission.

There was also a prehistory to Chadwick's discovery. In 1930 Walther Bothe and Herbert Becker at the University of Giessen in Germany had bombarded beryllium with alpha particles from a polonium source and used a Geiger counter to observe the radiation coming from the beryllium. From the penetrating character of that radiation, they thought that it must be gamma rays of unprecedentedly high energy.

The Bothe–Becker observation was soon followed by similar experiments by Frédéric and Irène Joliot-Curie in Paris. But they placed sheets of various light elements in front of their detector and found that protons were being ejected from the sheets. At one point they used a sheet of paraffin and, to their surprise, found a greatly increased count rate for the protons.

The Joliot-Curies attributed that observation to a type of Compton scattering of gamma rays in the paraffin. But Chadwick did not think that possible and decided to conduct his own experiments. Unfortunately, he didn't have a good alpha source and the frugal Rutherford refused to authorize the purchase of a new one. Luckily, a colleague told Chadwick of a cache of old radon ampules at a hospital in Baltimore, Maryland. The radon in those ampules had decayed to produce a sizeable quantity of polonium. The hospital was pleased to donate them to Chadwick, and the polonium became Chadwick's alpha source.

The setup for Chadwick's discovery experiment is shown schematically in figure 3. He determined the energy of the ejected alpha particles to be a monochromatic 5.7 MeV. Then from the kinematics of the presumed elastic collisions that ejected protons from the paraffin, he concluded that the radiation from the alpha-bombarded beryllium target could only be neutral particles with mass close to that of the proton. He had discovered the neutron, liberated in the reaction

$$^{9}\text{Be} + {}^{4}\text{He} \rightarrow {}^{12}\text{C} + \text{n}.$$

Could the neutron simply be a bound combination of a proton and an electron? That conjecture was ruled out by the fact that molecular spectroscopy had determined the spin of the nitrogen-14 nucleus to be 1 (in units of $\hbar$). If the neutron were nothing but a proton with a bound electron, the ^{14}N nucleus (charge +7) would consist of 14 protons plus 7 electrons. It was, however, already known that both protons and electrons have spin ½. So there was no way that 21 of them could combine to produce a net spin of 1. One had to conclude that the neutron also had spin of ½. It was thus accepted that the neutron was an elementary particle in its own right.

In 1935 Chadwick received the Nobel Prize in Physics "for the discovery of the neutron." During World War II, he became head of the British mission to the Manhattan Project, which ultimately put nuclear fission to cataclysmic use.

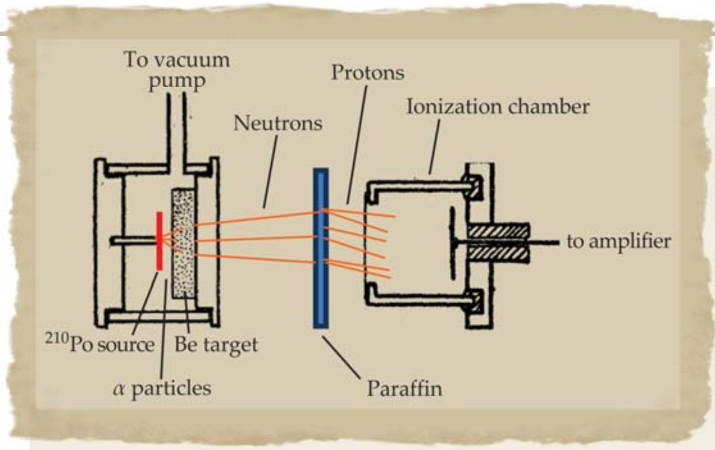


Figure 3. James Chadwick's setup for his 1932 discovery of the neutron. The polonium-210 source produces 5.7-MeV alpha particles that break up in the beryllium target to yield free neutrons, which then collide elastically with protons in the hydrogen-rich paraffin that screens the downstream proton-detection system. (Adapted from ref. 2.)

The positron

The third of 1932's historic discoveries came in August, when Anderson, working under the supervision of Robert Millikan at Caltech, discovered the positron. Anderson was observing cosmic rays with a cloud chamber mounted vertically inside a magnetic field. Bisecting the chamber was a horizontal lead plate. From the curvatures and track lengths of cosmic-ray trajectories passing through the plate, Anderson concluded that about a dozen of them, collected over several months, represented positively charged electrons, which he called "positrons." At the University of Cambridge, Patrick Blackett and Giuseppe Occhialini were seeing much the same thing. But Anderson's September 1932 report of his first few events[3] beat them to the punch.

The existence of the positron had, in a sense, been predicted in 1928 by Paul Dirac. His relativistic wave equation for the electron had negative-energy solutions that suggested the existence of positively charged electrons. In 1931 Dirac definitively predicted such "anti-electrons," which would mutually annihilate with ordinary electrons. That's an early example of the successful prediction of a new particle from theoretical principles. Indeed, in the same paper Dirac predicted the existence of the antiproton, which would not be seen for another 24 years.

In 1936 Anderson received the Nobel Prize in Physics "for his discovery of the positron." He shared the prize with Victor Hess, the discoverer of cosmic rays. That same year Anderson and his graduate student Seth Neddermeyer once again used a cloud chamber exposed to cosmic rays to discover another new charged particle—the muon.

Nuclear physics

Although they had different electric charges, the proton and neutron had remarkably similar masses. Heisenberg suggested that they could be regarded as alternative states of a two-level fermion, subsequently called the nucleon. All nuclei would then consist only of nucleons. Heisenberg proposed that the degree of freedom that distinguishes protons from neutrons, later named "isotopic spin" or simply isospin, should be treated on the same footing as spatial and spin coordinates in constructing fully antisymmetric many-nucleon wavefunctions. Isospin remains an important organizing principle of nuclear and particle physics.

The deuterium nucleus, called the deuteron, is a boson with spin 1 and isospin 0. The strong nuclear force that binds nucleons together acts only over distances of order 10^{-13} cm. In 1934 Rutherford and Mark Oliphant bombarded deuterons with neutrons and thus created tritium, the third hydrogen isotope. It decays to ^{3}He plus an electron with a half-life of 12 years.

Nowadays tritium is produced in nuclear reactors, in the heavy water used to slow down (moderate) the reactor neutrons. And tritium will have a key role in the fusion reactors of the future. Because tritium's two neutrons increase the attractive force between its nucleus and others nearby, the triton fuses much more easily with other light nuclei than does the ordinary hydrogen nucleus. Thus the preferred reaction foreseen for fusion power reactors is

$$\text{D} + \text{T} \rightarrow {}^{4}\text{He} + \text{n}.$$

It's also the principal reaction in thermonuclear weapons.

Accelerators

The year 1932 also witnessed the first use of accelerators to study nuclear reactions. John Cockcroft and Ernest Walton at the Cavendish Laboratory had been developing circuitry to produce extremely high voltages. (The opening figure on page 44 shows the two young men flanking Rutherford.) Their scheme was based on a series of capacitors and diodes that rectified AC to DC. By early 1932 they had achieved an output voltage of 600 kV, which they used to accelerate protons.

The target was a sheet of mica coated with lithium. When the protons struck the lithium target, the reaction

$$p + {}^{7}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

created two alpha particles flying off in roughly opposite directions. The "swift protons," as Cockcroft called them, had made lithium nuclei disintegrate.[4]

A few months later, Ernest Lawrence and Stanley Livingston at Berkeley disintegrated lithium, boron, and fluorine by bombarding them with 1.2-MeV protons from Lawrence's cyclotron. By repeatedly accelerating the orbiting protons across the same voltage, the cyclotron was the first accelerator that could achieve high particle energies without the need for high voltage.

The experiments on the disintegration of lithium provided the first quantitative test of Einstein's mass–energy relation $E = mc^2$. Because the nuclear masses were well known and the kinetic energies of the emitted alphas were measurable, the mass–energy relation could be verified.

With the advent of accelerators, physics research was changed forever. Lawrence was awarded the 1939 Nobel Prize in Physics "for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements." Cockcroft and Walton shared the 1951 prize "for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles."

Neutrons and deuterons at work

With the discovery of nuclear fission, both neutrons and heavy water were soon put to work to develop nuclear power and nuclear weapons. Experiments by Enrico Fermi and others showed that reactions between neutrons and nuclei were greatly enhanced if the bombarding neutrons were slowed to thermal velocities. In pondering the difference between fission in uranium and thorium early in 1939, Niels Bohr came to the realization that it was only the ^{235}U isotope, less than 1% of naturally occurring uranium, in which slow neutrons induce fission (see figure 4).

Physicists in several countries, some potential adversaries, immediately considered the possibility that the fission process would, on average, liberate enough neutrons to unleash a chain reaction. That possibility was dramatically realized when Fermi's team, working in great secrecy under a grandstand at the University of Chicago, achieved a sustained chain reaction in December 1942. That was the first major experimental accomplishment of the Manhattan Project, which had been organized by the US government to develop nuclear weapons.

Fermi's first "pile" used 46 tons of unenriched uranium interspersed with bricks of highly purified graphite that served to moderate the fission neutrons. Fermi and Leo Szilard filed a secret US patent application for the "neutronic reactor" in December 1944. The patent was publicly granted in 1955.

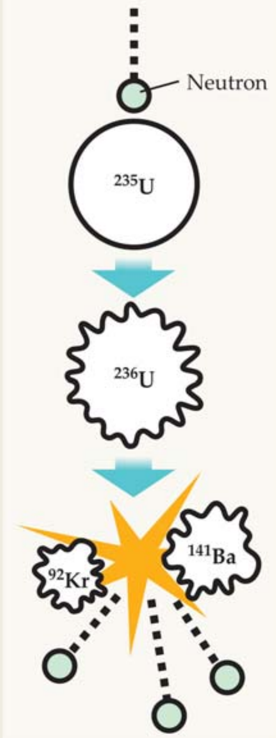


Figure 4. Fission of a uranium-235 nucleus is induced by an incident neutron, whose absorption briefly raises it to an excited state of ^{236}U. In this example, the excited nucleus splits into fast-moving fission products barium-141 and krypton-92, and releases three free neutrons.

Barely two and a half years after the Chicago team achieved a sustained chain reaction, the first bomb-test device was exploded at the Trinity test site in New Mexico. The Trinity bomb's fission fuel was plutonium-239, created in the Manhattan Project's enormous factory arrays of uranium reactors. Less than a month after the test of the plutonium bomb, another one was exploded over Nagasaki, Japan, on 9 August 1945. The ^{235}U bomb that leveled Hiroshima three days earlier had a much simpler firing mechanism that required no prior test.

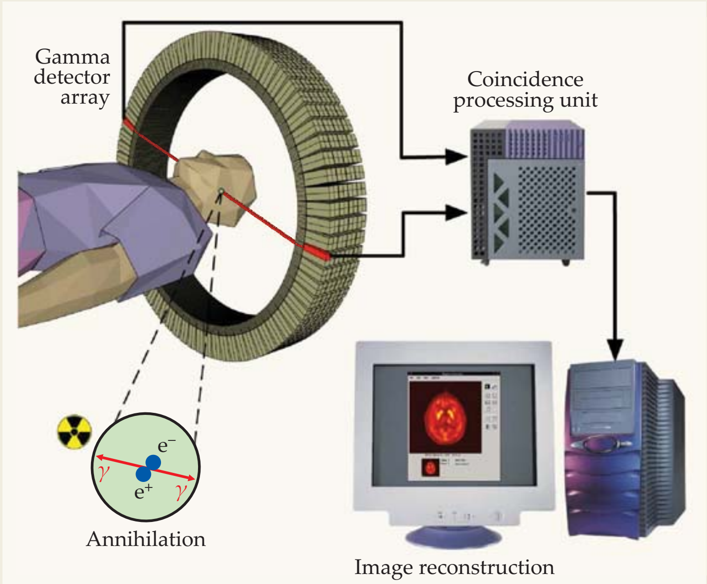
German scientists, led by Heisenberg, had pursued a different route in quest of a reactor. They wrongly believed that industrially produced graphite would inevitably be too contaminated by neutron absorbers such as boron to serve as a moderator. The best alternative moderator was deuterium. Heavy water was being produced on a large scale at Norsk Hydro's Rjukan plant. The plant, situated beside a large waterfall, had been producing ammonia by electrolysis since the early 1900s. With the discovery of deuterium, Norsk Hydro realized that the plant could produce heavy water as a byproduct. By 1935 the facility was shipping 99% pure heavy water to countries throughout Europe for scientific experiments. When the Germans invaded neutral Norway in April 1940, they promptly seized the plant and began shipping large quantities of heavy water to their weapons labs.

By 1942 the Americans and British were convinced that heavy water was a critical component in the German nuclear effort. Though deuterium itself could not be used in a fission bomb, reactors would be important for obtaining critical fission data *and* for producing ^{239}Pu, which both sides understood to be a potential fission-bomb fuel that might obviate the enormous difficulty and expense of separating ^{235}U out of natural uranium.

So the Allies undertook to disable the Norsk Hydro plant. Because it was nestled among steep mountains, aerial bombardment was difficult. But eventually Allied bombing forced the Germans to abandon the plant. To salvage the stock of heavy water on hand, they undertook to ship it to Berlin by rail. To cross a lake near the plant, the railcar had to be loaded onto a ferry. But the Norwegian underground had gotten wind of the shipment and planted a bomb aboard the ferry. It exploded in mid-journey, sinking the ship and its cargo, but also taking the lives of 14 Norwegian civilians.[5]

After the war, the US undertook the development of nuclear-fusion weapons—that is, hydrogen bombs. Their key ingredients are deuterium and tritium. The first test of such a weapon was carried out in 1952, on Enewetak Atoll in the Marshall Islands. The test required about 1000 liters of liquid deuterium, which was produced at the NBS cryogenics laboratory in Boulder, Colorado. The facility had been developed expressly for that purpose by Brickwedde, who had made the first-ever samples of deuterium in milliliters of heavy water 21 years earlier.

Figure 5. Positron-emission tomography (PET scanning) of a subject's head. An array of gamma-ray detectors surrounding a plane of the head maps the accumulation of injected molecules carrying a radioactive positron-emitting tracer. A decay positron (e$^+$) promptly annihilates at rest with a nearby electron to create a collinear pair of 511-keV photons (γ) that reveal their precise origin along their common flight line by the subnanosecond difference between their arrival times on opposite sides of the detector array.



Applied antimatter

Positrons can be produced in significant quantities by radioactive sources and electron accelerators. Nowadays they have a variety of scientific and practical uses. High-energy electron–positron colliders have made great contributions to fundamental particle physics. Synchrotron light sources often use beams of positrons rather than electrons because positron beams repel troublesome positive-ion beam impurities. Despite its brief lifetime, positronium—the electron–positron bound state—is an important vehicle for precision tests of quantum electrodynamics by means of high-resolution laser spectroscopy.

The most familiar practical application of positrons is in positron-emission tomography, called PET scanning. This medical imaging technology lets physicians look for tumors and monitor metabolic activity in living tissue. A patient is first injected with a tracer—specific biological molecules carrying a positron-emitting isotope. Then the radiologist looks for accumulations of that molecule in the patient's body by locating the resulting electron–positron annihilation sites.

A decay positron quickly comes to rest and annihilates close to the emitting molecule, creating a characteristic back-to-back pair of 511-keV gamma-ray photons. Their arrival positions and times recorded at a detector array surrounding the patient reveal the positron emission site. The technique is illustrated in figure 5.

The positron-emitting tracer is made by irradiating an element with protons from a dedicated local cyclotron. The radioactive element is then incorporated into the biological material. A common tracer is glucose incorporating the radioisotope carbon-11, whose half-life is 20 minutes.

Different tracers are used to probe different organs. One of the main applications of PET scanning is the detection of brain cancer. It also lets researchers study metabolic activity under various circumstances in different parts of the healthy brain.

Epilogue

During a family reunion last summer, one of us (Clark) discussed the extraordinary discoveries of 1932 with his uncle, a retired professor of mechanical engineering. The uncle was surprised to learn that he had been born a few years before the neutron was discovered. There are still living connections with that remarkable and portentous year.

Parts of this article are adapted from an article by the authors on the optical discovery of deuterium in the May 2012 issue of Optics and Photonics News*.*

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