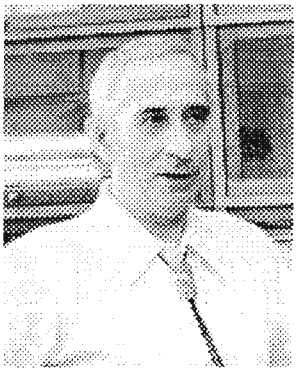
General

LANL Order, Accelerators (Brief history of @ LANL)

From the War Years to the Beginning of the Energy Crisis

Richard F. Taschek, P-Division Leader (1962-1970)



The discussion immediately below generally follows the more detailed, but still sketchy, report from the 40th anniversary volume Project Y: The Los Alamos Story. The primary emphasis is on the transitional and evolutionary scientific programs in the Physics (P) Division immediately following the war years.

During the wartime years 1943 to 1946, P Division, which was initially the Research (R) Division, acquired and generated responsibilities mainly in nuclear physics and supported the theoretical and calculational efforts to design nuclear devices that eventually led to field-use weapons—the Laboratory's mission. But the data base in many areas of science was poorly known or absent. Theoreticians and designers understood, however, that certain data have high priority and high sensitivity to the accuracy of the information. The requirements were fairly well known, but the acquisition of data of known high accuracy was very difficult for numerous reasons. Sources of "Cast" neutrons were known from programs under the Office of Scientific Research and Development at the University of Wisconsin, University of Minnesota, University of Illinois, and elsewhere before the Manhattan District was formed. The neutron energies available covered a good share of the spectrum of neutrons emitted in the fission process. However, the "point" sources were generally of low intensity. The neutron flux measurements were primitive, and knowledge of the accuracy was difficult to obtain. During this period, methods were developed to measure the cross sections for the fission of 235U and 23% from some tens of keV to about 3 MeV accurately enough for early calculations. At about the same time, the fission neutron spectrum could be measured by nuclear emulsion and other techniques and applied experimentally.

In addition to determining the fission cross sections of 235U, 238U, and 239pu as a function of neutron energy, data were also required on the scattering of neutrons from heavy metals. These metals were being considered as possible reflectors for the fissile weapons assemblies. Lengthy measurements were made at several incident neutron energies on cylindrical slabs of different thicknesses to include effects of angular distributions and inelastic scattering. This effort resulted in somewhat "integral" phenomenological data needed for design purposes.

Data of the kind mentioned above were most directly obtained by the use of electrostatic accelerators, which could bombard target elements of lithium or deuterium with protons or deuterons, respectively, to give monoenergetic

neutrons over wide ranges of energy simply by changing accelerator voltage.

The Cockcroft-Walton (CW) accelerator borrowed from the University of Illinois had a peak voltage of about 300 kV and a large beam current. It was very useful in producing monoenergetic neutrons from deuterons on deuterium targets—2.5 MeV at 90¾ to the beam line and about 3.1 MeV at 0¾. Late in 1945, beam and target technologies had become sufficiently developed so that l4-MeV neutrons of very great source strength could be produced by bombarding tritium-ice, or Zr (T), targets with deuterons using the T(d,n)3He reaction, which has a very large cross section at low energies.

With the development of thin-window gas targets for either deuterium or tritium, the borrowed electrostatic accelerators from the University of Wisconsin could be used with tritium targets to produce neutrons above 14 MeV to about 17 MeV. With deuterium in the targets, the neutron range was about 3 to 6 MeV with the accelerators available. Because the Wisconsin "Long Tank" had to be returned to the university, a great gain from the tritium targets came from another nuclear reaction. The T(p,n)3He reaction could produce a neutron energy range paralleling the 7Li(p,n)7Be reaction used with the Long Tank's higher voltage. The "Short Tank," which stayed at Los Alamos, could now handle this need. Considerable work, which did not reach fruition until almost 1950, was required to produce an easily usable, reliable capability for these reactions. During this period, another Short Tank was built to cover the work load because research involving charged-particle reactions among the light nuclei was becoming a fairly sizable program.

At this time, the cyclotron (borrowed from Harvard University) was not a useful competitor to the linear machines in producing monoenergetic neutrons in the fission-neutron energy range. It could, however, produce short, intense neutron bursts with spectra ranging from fractional eV energies to around 10 MeV. These intense bursts were particularly valuable for measurements in the thermal to low-keV energy ranges where the neutron time-of-flight technique could be used for conducting nuclear structure experiments or for studying the behavior of neutrons as a function of time in physically large assemblages, i.e., the so-called "integral" experiments. Values of , the average number of neutrons per fission, were measured at the cyclotron for thermal (1 to 40 eV) neutron fission and at the electrostatic accelerators for 300-keV neutrons. Although these experiments indicated no neutron energy dependence of the approximately measured value of 2.5 neutrons per fission, they were probably not very reliable (as shown in later experiments).

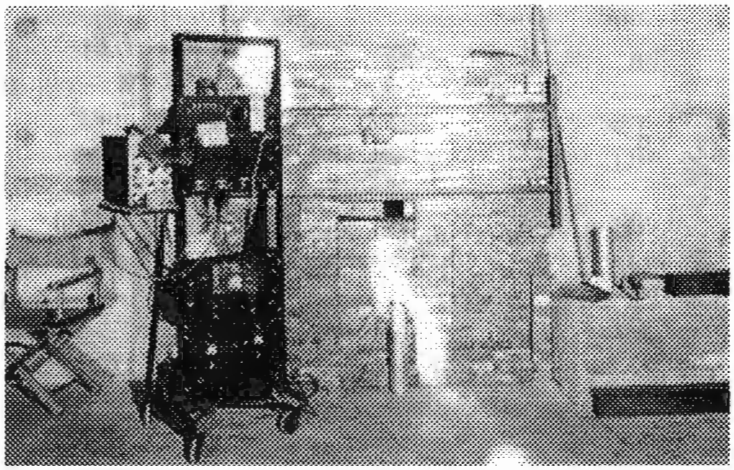
One of the most difficult quantities to measure was the capture of fast neutrons with the emission of one or more gamma rays, which resulted in a new isotope. Although radiochemistry was the technique of choice and excellent for thermal and epithermal neutron energies, the experiments were difficult and had poor accuracy for the weak sources of fast neutrons. Other techniques were even worse, and this area of fast neutron physics remained unchanged until much later.

The inelastic scattering of fast neutrons from nuclei of interest results in an energy loss of the scattered neutron; the energy loss of neutrons scattered from light nuclei elastically is not included. The techniques were not yet well developed. Although the cross-section measurements were needed, most of the methods tried depended on the energy of the inelastically scattered neutron. This

energy was determined with a particle counter that had a reaction cross section with a desirable energy dependence, for instance, approaching an ideal step function. The measurements were set aside to await future development. Time-of-flight techniques were beginning to be examined in detail as a result of advances in fast electronics and multichannel-pulse analyzers.

Another measurement of great importance to the further development of nuclear weapons was the energy spectrum of the neutrons emitted in the fission process. As mentioned above for inelastic scattering, the key problem was how to determine the energies of these neutrons. Fortunately, the sources of relatively pure fission neutrons could be quite strong (as opposed to those from inelastic scattering). Because of this great strength, special photographic emulsions developed in England could be used to record proton recoils from the fissionable source neutrons, which could then be translated into a spectrum. This technique, which was developed early by Hugh Richards, was pursued effectively by Louis Rosen with a cadre of well-trained plate readers. He used the method in the laboratory and for nuclear-weapons tests.

Because considerable emphasis had been placed on the properties of devices that produce fast neutrons, pulsed neutrons, fission neutrons, and slow neutrons, the development in Fermi (F) Division of a low-power "Water Boiler" must not be overlooked since it was another intense source used in the continued production of the data base for neutron-physics research. During this early period, the low-power Water Boiler was built and used mainly to study the technology, engineering, and other properties of the reactor itself. This earlier version established the design criteria for the high-power version of the final Water Boiler.



The Water Boiler reactor, the world's first enriched uranium reactor, was used as a research tool during the development of the bomb.

The Kellogg Years (1946-1962)

The Laboratory experienced rapid changes following the end of the war, particularly because most of the senior scientists returned to their home academic, industrial, or other positions. Because many younger scientists also took positions in the "outside world," these losses after the war greatly affected the remaining staff at Los Alamos. The uncertain future of the Laboratory was widely discussed

with speculations ranging from the imminent total closure of the Laboratory to establishing it as a federal laboratory with continuing military objectives. Other options, besides military, were also considered. Staff recruitment became a primary objective, although there was some concern that few outsiders would be interested in working at the Laboratory.

Rather quickly, beginning in August 1945, R Division under Robert Wilson was joined by the Water Boiler side of F Division and became P Division under John Manley (and briefly under John Williams). Manley brought in Jerry Kellogg from Columbia University, who then became Division Leader in July 1945. Kellogg had just finished major research on the quadrupole moment of the deuteron; he was a highly desirable addition to the Laboratory. Kellogg assigned Alvin Graves, a senior staff member, as his alternate. It was assumed that P-Division staff members would, at least initially, round out and continue the work being done at the end of the war—that is, finish some experiments, improve data in certain areas, and look to the future. More than any other activity in the Laboratory, P-Division's "directed" research resembled basic research in academic institutions in the same or parallel subdivisions of physics. Such research was also done in the Chemistry and Metallurgy (CM) Division. The policy of "noncompartmentalization" at staff level in the Laboratory led to excellent capabilities and accomplishments.

Early in 1946, Laboratory administration began to think seriously about moving from Central Mesa to South Mesa across Los Alamos Canyon. This was to be a gradual transfer, but some activities were already urgent, for instance, the work of the Chemistry and Metallurgy Research (CMR) Division. Almost simultaneously, a major improvement in the capability of an electrostatic accelerator, to be designed and built in-house, was justified, approved, and undertaken because commercial suppliers did not yet exist. A double-pressure region for this machine, designed by Joe McKibben and his staff, was expected to provide maximum voltages in the 8- to 10-MV region. Funding for this large effort was at that time readily obtained from Congress and the United States Atomic Energy Commission (AEC), now the Department of Energy (DOE).

The continuing research programs in the electrostatic-accelerator group and the CW accelerator were combined administratively in Group P-3, and the new machine design activity under McKibben became Group P-9. The CW group by this time had produced very high source intensities of 14-MeV neutrons from the D-T reaction. Although the electrostatic and CW accelerators were at opposite ends of a long hallway, some of the detectors at the electrostatic accelerator received serious background radiation from the 14-MeV neutrons, which air scattered and were directly incident on the instrumentation. This was particularly true for a large-volume scintillation counter that had very high sensitivity to neutrons, i.e., about 80% of the neutrons incident on it produced a signal. Several design options were considered for reducing this background-radiation problem particularly because we knew that we would be moving to South Mesa in the near future into a new building. Thus, the intent was to build a long hall connecting the electrostatic and CW accelerators, each of which would additionally have a high, thick concrete shield wall between the accelerators and operating personnel. Background radiation at one accelerator produced by the machine at the other end of the hall was also greatly reduced by these high shield walls. By this time, the CW accelerator had reached total source strengths of about 1014 n/s (neutrons per second), which at 1,000 ft from the source would give about 104 n/cm2s if unshielded. A new CW machine was purchased from a

commercial vendor—instead of 300 kV, 500 kV was now available.

These problems were mitigated by building the portion of the planned physics building that would house two small electrostatic accelerators first; the move from the old technical area was made in 1951. The new long hall was designed to accommodate laboratories on one side and office space on the other; it was therefore built more gradually. The cyclotron was located at the end of another hallway at right angles to the one discussed above in an area of the building that is now the west wing. The central core of this building is still occupied by P Division. This building was constructed of reinforced concrete with thick walls to withstand a Hiroshima-size nuclear explosion! That type of construction was not followed for very long. The new 8-MV electrostatic accelerator was under construction in an open area about 300 m from the physics building where it still stands, and the new CMR building was already finished and in use.

The realization that all of the physical and other steps taken were toward a strong permanent scientific Laboratory produced a euphoric feeling among the staff. This stimulated considerable creativity toward new concepts for experiments and programs.

In P Division during the initial years of Kellogg's tenure, experimentalists were urged to do, and began doing, more painstaking research using existing methods, and they continuously developed new and better approaches to difficult measurements. For example, P-Division staff members redesigned a large, liquid scintillation counter originally conceived and built by the Health Research group, which used the device to detect very low levels of radioactivity in humans. Fred Reines, Clyde Cowan, and colleagues built a version of this whole-body counter to detect the "elusive" neutrino. The electrostatic-accelerator staff meanwhile built a version that could detect nearly all neutrons emitted by a single-fission event. This last effort involved the counter referred to above, which was highly sensitive to background radiation from natural sources and from the CW accelerator.

Because this huge counter's sensitivity was so large, fission produced by weak primary fast neutron sources could be used to determine the average number (number of neutrons/fission) as a function of energy. Thus, the old standing problem of getting the energy dependence of was solved. These experiments with the large-volume scintillator were not simple and did require sophisticated electronics for timed detection relative to pulsed neutron bursts.

An important event in P Division in late 1946 was the initially hesitant, but then rapid and continuously controlled, declassification of much of P-Division research. The remainder of the Laboratory was not affected so quickly by this activity. For P-Division staff, it was the beginning of the return to traditional scientific communication via the American Physical Society's (APS) Physical Review publication and other peer-reviewed publications. In 1947, several members of P Division presented 10-minute papers at the Chicago meeting of the APS. In 1948, a full-length paper appeared in the Physical Review on the 7Li (p,n)7Be neutron source. Equally important, staff members began to attend scientific meetings, both domestic and foreign, where the scientist-to-scientist exchanges opened doors that had been closed for too long. Graduate students and new scientists who had recently earned PhDs (especially from former members of the Laboratory) started very slowly to be recommended to Los Alamos even

though the very best were recommended to academia first. Communication between former friends and colleagues was central to this activity (the Old Boys' Club syndrome!) and very valuable to us.

Declassification did not come easily to Los Alamos work. In some cases, whole subdisciplines of physics like the controlled-thermonuclear-reaction (CTR) research, now known as magnetic fusion, remained classified, James Tuck's CTR concept (referred to by co-workers as "Friar Tuck and the Sherwood Forest" project) for a self-magnetic pinching effect in a plasma led to work on a prototype experimental device to burn deuterium, called the "Perhapsatron." There was great interest in this project at the Laboratory, and it was not hard to assemble a fine staff of innovative scientists. All work in controlled fusion of light elements was classified until about 1956. Although administratively in P Division this research program was physically separated from the nuclear-physics area, CTR became a distinguished program and was well supported until recently.

Sherwood's linear machine. The open-ended quartz tube was placed in the compression coil between two rows of capacitor banks. The two outside banks (right) were used to energize the magnetic mirrors. The curved sector of Scyllac is shown just beyond the wall. Consideration was given to the question as to whether a very long Scyllac could compete with a toroidal device.

Almost from the very beginning of the Los Alamos CTR program, emphasis was in the direction of pulsed, very hot, high-density plasmas. This approach was quite unique in the national program and not highly thought of in most of the other laboratories. Yet the first true laboratory-produced thermonuclear fusion occurred at Los Alamos. This story by Jim Phillips can be found in the 40th anniversary volume Project Y: The Los Alamos Story.

Experiments using the theta (q) pinch approach culminated in the toroidal Scyllac, which after about three years of full-scale research was killed because of the high voltages required and the complexities of plasma stabilization. As more sophisticated knowledge was acquired from experiment and theory during the 1970s, a return to z-pinches led to the reversed-field pinch and later to compact toroids. Some of these configurations also used q pinches, which were very successful in producing very hot (a few million degrees), dense plasmas in the few millisecond regime. Good support for the reversed-field pinch was obtained until about 1990 when a major cutback of the Los Alamos program and of most other national efforts occurred.

Magnetic fusion is very likely the most difficult applied scientific and technological problem that mankind has attempted to carry out to date. Its

solution is clearly of great importance to our need for a clean, safe, and inexhaustible energy source. Most of the Western nations and the U.S.S.R. established one or more laboratories primarily devoted to researching the subject. During the "classical-subject" period, the United States pursued several approaches to find a solution to the problem primarily in its AEC laboratories, each of which had its own set of subapproaches. Strong competition in methods of heating, containment, and stability of plasma developed within individual laboratories and with outside national and international laboratories. In our country, budget control (initially by objective evaluation of programs) began to shift toward management from Washington, D.C., with time/accomplishment (milestone) charts, which were patently unrealistic. These charts were so unrealistically short in time that the accomplished knowledge was left far behind. The political response to this was the beginning of budgetary cutbacks and limitations, which merely exacerbated the real difficulties experienced by the scientists. Somehow, the lessons from the fast-fission-reactor-program debacle were not known, or they were ignored or shoved under the rug. The results are similar—a shutdown of promising ongoing programs in all DOE-supported laboratories except for the politically correct one or two. In the case of the sodium-cooled, fast-fission-reactor program, all but one effort was killed, and then the sodium-cooled reactor decayed away on the banks of the Clinch River (a tributary of the Tennessee River) for want of viable alternatives or innovative scientists. The fission reactors, which now should be providing the transitional electrical energy source between CO2-producing fossil fuels and misrepresented magnetic-fusion energy, are being seriously hampered by politicians and others for their own ends.

A marker event of great consequence to the scientific community as a whole and especially to those working in nuclear-energy programs was the First Conference on the Peaceful Uses of Nuclear Power held in Geneva, Switzerland, in 1955. This conference was initiated by the United Nations General Assembly for the purpose of "exploring means of developing the peaceful uses of atomic energy through international cooperation." Several members of the Laboratory (and P Division) attended this meeting; some of our people presented papers. This conference introduced our staff to other scientists and other research centers, to new ideas, and to the birth of the International Atomic Energy Agency. The excitement on the international scale was tremendous, and although it did not all lead to what one might have hoped, the desire was there. Unfortunately, the will was weak under national political pressures.

It is impossible to discuss all of the events of the 1950s and 1960s in a fashion that would do these decades justice. A quick overview of some of the activities will indicate something of the dynamism of this period. A few programs will be discussed in fuller detail.

A strong point should be made that P-Division personnel always considered themselves available for the work on the programmatic side of the Laboratory, particularly for nuclear-weapons tests. For these programs, P-Division scientists would curtail or drop their ongoing activities in long-term research to design and build detectors or other devices for diagnostic field measurements, which they would then carry out on test shots primarily at the nuclear test sites in the Pacific islands. The tradition for this had already begun before Trinity and continued thereafter. Greater responsibilities were also acquired by individuals who worked on the first thermonuclear-weapon experiment and the later full-scale devices, which led rather quickly to specific weapons. Harold Agnew, Ben Diven, and

Wally Leland took on such programs and carried them to successful conclusions; this story should soon be written in full (unclassified) detail. As further and different P-Division work is discussed below, brief comments will be made about whether and how these activities had fit in with the primary responsibilities of the Laboratory.

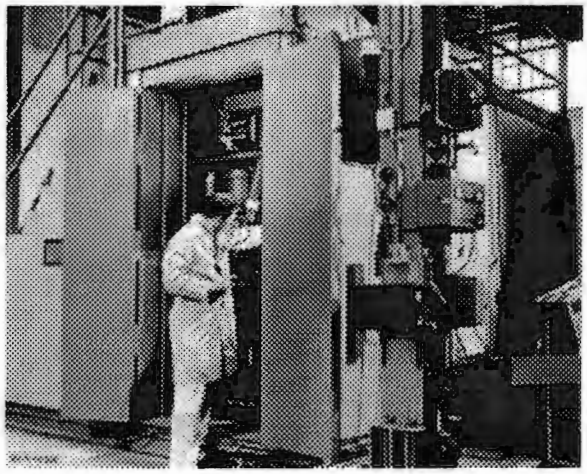
Work on the 8-MeV electrostatic accelerator progressed continuously during this period; construction began on South Mesa to house this accelerator and two 2.8-MeV electrostatic machines.

A strong electronic research and development group (P-1) had been established by Darol Froman, continued by Ernie Titterton, and followed by Bill Hane and John Lamb. The work performed by this group was thought of as overhead or indirect-cost service of great strength and versatility in Laboratory-wide use. In-house electronics groups in divisions were frowned upon.

Fission Reactors

As discussed in the 40th anniversary volume, the Water Boiler in its 25-kW revised version became a "workhorse" for diagnostics and basic research for many parts of the Laboratory. Clementine, a plutonium "fast" reactor (plutonium metal fuel rods and mercury cooling) was built by Phil Morrison, Dave Hall, and staff. This reactor helped scientists answer questions concerning such systems.

Between March 1949 and December 1952, Clementine was operated at a power of 25 kW. In early 1950, the mercury coolant showed contamination with alpha-emitting products, probably plutonium and uranium. A uranium spacer rod found ruptured was believed to be the source of plutonium emission (via breeding in the uranium). Eventually, continued operation for over a year produced enough distortions and corrosion in the fuel-pot area so that when alpha radiation was again observed in the coolant in December 1952, the reactor was shut down. Disassembly was accomplished with less than tolerance exposure and the barely detectable escape of plutonium by the summer of 1954, as related by Ed Jurney, who was involved in this operation.



Clementine's north face showing the enclosure for the mercury cooling system.

The successes and limitations of the 25-kW Water Boiler and Clementine encouraged thinking about what would be possible if a considerably higher-power reactor could be obtained for the Laboratory. An in-house project was established to build a water-cooled, uranium-enriched, fuel-element reactor of

about MW. The design of the reactor and fuel elements was based on the Materials Test Reactor (MTR); the fabricated fuel elements were supplied by Oak Ridge National Laboratory. The new reactor became critical in 1956 and ran first at 800 kW for about one year, then at 5 MW for several years, and finally at 8 MW after more cooling capability was added. Known as the Omega West Reactor because of its location, it has been used for outstandingly worthwhile research and development.

Unfortunately, not all of the research done with the Omega West Reactor can be reported herein. In addition to P-2, P-Division's in-house scientific group, research and development staff from other divisions brought some of their problems to the reactor for resolution. The accelerators, which produced excellent results in general, were also used by other groups when needed. One of the most continuous users of the Omega West Reactor was J Division, the nuclear test division, for obtaining radioactive debris irradiations as needed for determining nuclear yields of the explosive devices detonated at the Nevada Test Site or in the Pacific islands.

Jerry Kellogg, who had provided wise leadership to P Division beginning in 1946, suffered a heart attack in the fall of 1958. He returned to active control of the Division in 1959, but unfortunately another attack of the same malady caused him to withdraw from P-Division activities; he became Research Advisor of the CTR program. I had been alternate Division Leader since January 1959 and, subsequently, became Division Leader in September 1962 with Louis Rosen as the alternate.

One of the outstanding scientific programs initiated in 1962 by Hank Motz, Bob Carter, and W. D. Barfield at the Omega West Reactor Facility was the measurement of gamma rays produced in thermal-neutron capture by beryllium and nitrogen. Neutrons inside of the Omega West Reactor shield fell upon a beryllium or nitrogen target where some were captured, and characteristic gamma rays were emitted. Some of these gamma rays passed down a collimator to a magnetic Compton spectrometer where a thin foil scattered gamma rays and produced recoil electrons. Coincidences of scattered gamma rays and electrons identify particular incident gamma rays. A magnetic field in the spectrometer allows energy measurements of a gamma-ray line to be made via the ejected electrons. Although the understanding of the design and use of this spectrometer is far more complex than can be related here, two points need to be made. First, the spectrometer requires a high flux of gamma rays. Second, obtaining a high flux of gamma rays requires a high-intensity neutron source—that is, a fairly high-power nuclear reactor such as the Omega West Reactor. If these criteria are satisfied, high energy resolution can be obtained (for instance, 0.3% at 10 MeV for the Omega West Reactor spectrometer). The initial experiments were performed with beryllium and nitrogen because of the relative simplicity of the gamma-ray spectra of these light nuclei. Gamma-ray spectra are then used to deduce energy-level diagrams for compound nuclei formed in neutron capture.

A classic paper published in 1967 on the energy levels of 166Ho was the result of an international collaboration of groups from Los Alamos, Germany (two groups), Denmark, California, Florida, and Sweden. The work was done in part at the home institutions and during visits to other institutions. At Los Alamos, gamma-ray spectra were obtained slowly by using the Compton spectrometer method and considerably faster by a pair spectrometer with a Ge(Li) detector. These methods of obtaining energy levels of nuclei were so successful that they

are still used at the Omega West Reactor Facility to obtain detailed knowledge of nuclear structure.

Under the direction of John Yarnell, a neutron diffraction spectrometer was set up at one of the beam ports of the Omega West Reactor. One of the first experiments performed with this apparatus was an attempt to explain some of the anomalous properties of liquid helium II. Lev Landau's theory proposed an energy versus momentum excitation spectrum, which could be checked by observing the scattering of neutrons with long wavelengths (about 4 Å) from liquid helium. Neutrons emerging from the reactor through a beryllium filter and collimator were incident on the liquid helium target and then on the neutron spectrometer, which measured the scattered neutron spectrum. The beryllium filter creates a spectrum of wavelengths with a sharp threshold just below 4 Å, rising to a wide band of longer wavelengths. The longer-wavelength radiation was incident on the liquid-helium target, and the scattered spectrum was measured at several temperatures.

The energy-momentum spectrum of the excitations in the liquid helium at 1.1 K had a very close resemblance to Landau's theoretical spectrum, which was first proposed in 1947. Landau was awarded the 1962 Nobel Prize in physics for his work on liquid helium. The definitive Yarnell, Arnold, Bendt, and Kerr experimental paper was received in 1958 and published in 1959. But before receiving his Nobel Prize, Landau had lost his capabilities because of a very serious accident. He accepted the prize in the hospital.

An outstanding series of experiments on the lattice dynamics of crystalline substances using neutron inelastic scattering and the determination of crystal structures in solids and of structure factors for liquids at very low temperatures were performed from 1963 to the early 1970s.

One experiment of particular interest shows the impact of basic science on technological problems. This experiment was a highly accurate measurement of the amount of heat produced by the decays of fission products with short half-lives; these decays control reactor shut-down temperatures and thereby the design and safety of the system. The method used was to measure the heat produced in a 52-kg copper block by the absorption of the radiation from the 235U foils, which had been immersed in a high-thermal neutron flux for a number of hours. The copper block was held at a temperature of 4 K by liquid helium, which was evaporated by the fission heat and used to accurately calculate this heat. Widely based physicists should read the publications about this classic experiment. Reducing the temperature of the copper block to about 4 K creates a quantum-mechanical effect that reduces the heat capacity of the copper block by a large factor and thereby reduces the thermal time constant to about 0.85 s. This finding resulted in a major correction made to the American Nuclear Society's standard for short-period decay heat—a standard that is used for, and has large implications in, the design and safety of light-water-cooled reactors.

The Los Alamos Cyclotron

In the new South Mesa home of P Division, space had been designed for the betatron near the cyclotron. The betatron from M Division was transferred to P Division under Bill Ogle and put in running condition, but no long-range program was established after Ogle joined J Division (he later became its

Divis[illegible] Leader).

The Harvard cyclotron in TA-l had been left in rather bad condition at the end of the war. It was put back into running condition by Joe Fowler and others and could accelerate protons to 9 MeV. In 1951, John Brolley, Stan Hall, and others published a paper on short-period activities from fission products of 235U using the intense source of broad-spectrum neutrons from protons on beryllium. A second paper by John Brolley, Jim Coon, and Joe Fowler reports on neutron-proton scattering at 27-MeV neutrons. In 1952, Tom Putnam measured the differential cross section for scattering of 9.48-MeV protons by 4He. This work was the last research using the original cyclotron and at TA-l.

In late 1952, Keith Boyer and Dick Stokes led a program to convert this accelerator (which is now in the P-Division building at SM40) to a variable-energy cyclotron by installing electric coils to compensate for saturation effects in the radial magnetic-field slope. Thomas shims improved beam focusing at small radii in the magnetic-field gap. The first beam was obtained near the end of 1954, and experimental research programs were begun in 1955. Protons could now be accelerated from 3 to 9 MeV, deuterons from 6 to 14 MeV, doubly charged 4He from 12 to 28 MeV, and eventually 3He from 9 to 27 Me V.

Sixty-eight publications that covered a wide range of nuclear physics were published between 1956 and 1966. Only a few of these can be touched upon in this article:

- Polarized protons were produced by elastic scattering of alpha particles by hydrogen (Louis Rosen and John Brolley).

- The endoergic reaction T + d Æ 3He + n + n - 3 MeV was observed (John Brolley, Louis Rosen, Stan Hall, and Leona Stewart).
- The thresholds of fission in 239Pu, 233U, 235U, and 238U were measured by using the (d,p) stripping reaction (John Northrop, Dick Stokes, and Keith Boyer). The (d,p) reaction introduces a neutron into the target nucleus, and the neutron energy can be determined from the energy of the observed proton. By measuring the energy spectrum of protons in coincidence with fission events, fission thresholds can be determined. The unique feature of these experiments allowed a first determination of fission thresholds for thermally fissionable targets such as 235U and 239pu. When tritium beams became available from the tandem electrostatic accelerator, the (t,p) reaction was used to study the fission process by adding two neutrons to the target nucleus.

- Polarized protons were scattered by various complex nuclei (Louis Rosen, John Brolley, Judy Gursky, and Leona Stewart).
- (3He,alpha) and (3He,T) reactions and their theoretical interpretations were done (Al Blair and Harvey Wegner).
- To characterize the ground- and excited-state systematics of light nuclei, cyclotron and tandem beams were used to produce reactions such as (d,p), (t,p), and (t,3He). Many new states were observed in nuclei such as 9Li, 12Be, and 22F. In addition, the first observation was made of the ground state of the 7He nuclear system, and its mass was determined through use of the 7Li(t,3He)7He reaction (Dick Stokes, Phil Young, and others).
- Extensive studies of the fission process, like the dependence of fission-

product mass yield on angular momentum, were made (Bob Leachman).

A Tale of Two Accelerators

Under the leadership of Darragh Nagle, an ad hoc group of interested staff members studied the problem of high-current accelerators. Around 1955, they had worked on a machine design for a high-energy accelerator, but this work was dropped as wide interest mounted in the United States and elsewhere for medium-energy accelerators with large beam currents. Joe Fowler had been a strong proponent for moving P Division in this direction especially after attending an international conference on variable-energy cyclotrons in 1962. A strong argument for the accelerator finally decided upon was that the 800-MeV, l-mA beam current could be used to produce a very strong source of muons and pions at the target. This alternative was particularly attractive to some Los Alamos experimentalists and to nearly all outside scientists in academic circles who did not have home access to such particles. Furthermore, the spallation neutrons, produced when the 800-MeV protons were incident on almost any target with a high atomic number, made a very intense pulsed-neutron source. Such a source was obviously of wide interest in the Laboratory and was compatible with the objectives of the weapons program. Detailed studies to determine which type of accelerator was most likely to succeed in meeting both varieties of objectives settled on a radio-frequency, cavity-type linear accelerator that produced a proton beam. This accelerator, which was later named the Los Alamos Meson Physics Facility (LAMPF), was expected to meet the 800-Me V, l-mA criterion without producing large amounts of radioactivity in the device itself. Strong competition was expressed by other government-supported laboratories, academic institutions, and private organizations. But after several review panels made in-depth evaluations of competing proposals, the Los Alamos proposal was approved.

Although the initiation of, and the early studies conducted on, the 800-MeV LAMPF accelerator had been done by P Division and most of the initial staff came out of P Division, LAMPF was intended to be a national research laboratory; therefore, its charter was separate from that of the Laboratory's. Louis Rosen became Director of LAMPF and remained so until the 1980s. During this period, he established a fine "outside" user group that produced a large research output. In addition, in-house research was performed by regular Laboratory full-time employees.

A highly respected research program was carried out in nuclear physics, meson physics, and the biosciences. Several specialized programs in neutron physics were also carried out; these programs eventually led to two ancillary facilities-the Weapons Neutron Research Facility and the Manuel Lujan, Jr., Neutron Scattering Center.

A few words should be mentioned about a second accelerator project that did not achieve implementation of the theory and experimental effort expended at Los Alamos. In the mid 1960s, physicists in the western countries began to bombard a wide variety of target elements with "heavy ions." Heavy meant anything above carbon nuclei. Heavy-ion physics became a branch of nuclear physics in its own right. This new field was stimulated in part by the hypothesis that superheavy nuclides might exist and have some very interesting properties. Various new accelerators were conceived for heavy-ion acceleration to high energies. One of

these as a spiral-resonator device studied in detail by Dick Stokes, Tom Tombrello, Phil Bendt, Bruce Erkkila, and others. The Director and staff members of the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, became aware of these spiral-resonator developments, and they visited Los Alamos to gather information. As a result, a highly versatile heavy-ion research facility was constructed in Heidelberg. This facility uses many spiral resonators to accelerate ions from a commercially built tandem facility.

The Electrostatic and Cockcroft-Walton Accelerators

Before and during the early 1950s (under stimulus from the very active thermonuclear-weapons program), research on the very light nuclei using the two 2.8-MV electrostatic accelerators and the new 500-kV CW accelerator was emphasized. British scientists (particularly Egon Bretscher, Tony French, and Mike Poole) used a low-voltage accelerator to bombard heavy-ice targets with tritons to measure low-energy cross sections of D(t,n)4He and of other related cross sections. These measurements had to be discontinued for a period after the war.

In the interest of the programmatic need for better understanding and accuracy of these cross sections, James Tuck (Group Leader), Jim Phillips, Emory Stovall, George Sawyer, and Wayne Arnold carried out definitive measurements below 100 keV and to 19 keV. In this case, deuterons were accelerated onto a thin gas target of tritium as a basic change from the earlier experiment. This experiment is an outstanding example of the care and attention used to obtain "absolute" results—indeed a classic example of such measurements. The range of deuteron energies covered was from 120 keV down to about 10 keV (actually to 7.5 keV).

Different techniques were used in an experiment (conducted earlier than the one mentioned above) on the old 2.8-MeV electrostatic accelerator. This particular experiment covered the energies from 80-keV tritons (roughly 53-keV deuterons) to 1,200-keV tritons—the range now thoroughly covers the resonance. These measurements are not of as high accuracy as those made by Tuck and his staff, but the cross sections of both experiments are within error limits in the overlapping regions. The electrostatic-accelerator research was conducted by Harold Argo, Harold Agnew, Art Hemmendinger, Wally Leland, and me.

While these experiments were going on, the new CW machine began to produce very high fluxes of 14-MeV neutrons; research was done on the scattering of these neutrons from hydrogen and deuterium and on the determination of the limits of fission taking place in heavy elements in general. The new electrostatic accelerator concentrated on the scattering of protons from tritium and deuterium. The reaction of tritons bombarding tritium to give 4He and two neutrons was also studied.

The acceleration of tritons had achieved a reasonably routine state by the middle of the decade. Ninety percent tritium was introduced into the ion source of the electrostatic machine. The ions formed could be accelerated to energies lying between a few hundred kV and an upper limit between 2.5 and 3 MeV. Tritium gas not converted to ions (namely most of it) was collected outside the accelerator by a pumping system consisting of a Swedish high-speed molecular pump followed by push-pull Toepler pumps, which put the gas into a collection tank. After several passes of the tritium through the acceleration cycle, the rather

impure gas was sent to the chemists for purification and then stockpiled for re-issue.

About 26 scientific papers on fast-neutron physics and charged-particle interactions among the lightest nuclei were published between 1947 and 1957. Most of the charged-particle research was done with the new 2.7-MV Short Tank.

The original Short Tank, under the direction of Ben Diven, continued emphasis on neutron cross sections and data that could be obtained by use of the large scintillation tank detectors. One of the first experiments was to measure "multiplicities" of neutrons emitted in fast-neutron fission of several fissile elements and of the neutrons emitted by several nuclides, which fission spontaneously. The probabilities of emitting 0 or 1 or 2 or 3, etc., neutrons per fission could be obtained, and the incident-neutron energy dependence of the average number of neutrons per fission was determined with excellent accuracy.

This experiment was followed by a more difficult investigation, namely to obtain the capture to fission ratios for 235U. The success of this experiment led to the measurement of radiative-capture cross sections for fast neutrons. These were measured using the scintillator-tank technique for 29 elements, including 238U and 235U at 7 neutron energies between 175 keV and 1 MeV. The last two experiments were done by Ben Diven, Jim Terrell, and Art Hemmendinger. The data obtained in these early tank experiments are of such a quality that the wartime requirements were more than fully satisfied.

Over a period of years, Ben Diven and collaborators also designed and implemented experiments, which used the intense source of neutrons from underground nuclear explosions to measure cross sections and other nuclear parameters for the heavy elements, some of which were highly radioactive. The first extensive measurements were done on the Petrel explosion in 1965, followed by Persimmon in 1967 and Pommard in 1968. The results are reported in the published literature. These data are of great value to both weapons and reactor design.

While much of the above research was going on, a systematic effort was being applied to produce better methods of neutron-energy discrimination by means of counters. In addition, improvements in fast electronics and pulse-height analyzers led to the development of the neutron time-of-flight technique. Between these methods, work at the new high-voltage Van de Graaff accelerator began to provide good data on elastic and inelastic scattering on many elements, including the fissile ones. The counter development was mainly done by Bob Allen, and the time-of-flight systems were accomplished by Larry Cranberg. Colleagues also involved in this activity were Bob Beyster, Martin Walt, Bob Day, and others. Inelastic-scattering cross sections were also done using either spherical shells surrounding the threshold detectors mentioned above or small fission counters. In-scattering and out-scattering canceled each other if the reaction was elastic, but inelastic scattering did not register. Mission requirements and basic science again were mainly fulfilled.

Upgrading the 8-MV Electrostatic Accelerator

In the mid 1960s, two developments, which influenced numerous research directions, took place at the 8-MV electrostatic accelerator. One of these was the purchase of a tandem Van de Graaff accelerator from Hivoltage Engineering Co.

The accelerator was put in the basement of the existing building that housed the 8-MV machine; the accelerator could either be operated separately or coupled to the 8-MV machine. This opened an energy range of more than double that of the existing accelerators. We also purchased an excellent magnetic-particle spectrometer that was based on a design by Harold Enge at the Massachusetts Institute of Technology. The spectrometer had very high energy resolution of nuclear-reaction products in this range of energies.

The second development of major impact was the production by Joe McKibben of a so-called Lamb Shift polarized-ion source. Although others had also made the same or similar sources, the Los Alamos version was clearly superior and several experimenters carried out detailed research on or with polarized light nuclei accelerated through the tandem accelerator. The successful tandem source stimulated the development of polarized targets of 1H2, 3He, and 59Co here and elsewhere. (Note that each additional nuclear parameter that can be controlled experimentally increases the capability of understanding the reaction dynamics.) The Los Alamos staff that originally carried out the experiments in this exciting area included Joe McKibben, Gerry Ohlsen, Paul Keaton, Jim Simmons, George Lawrence, John Hopkins, John Gammel, Wally Leland, Bob Watt, Don Dodder, and George Keyworth. At the International Symposium on Polarization Phenomena in Nuclear Reactions in 1970, 33 Los Alamos papers out of about 200 were presented by this group.

Monitoring Nuclear Weapons Explosions from Space and Space Physics

In 1957, Sputnik I created a great surge of interest in the new, rapidly developing field of space science. P Division was called in briefly to help clarify what caused damage to the solar cells of an early United States satellite. Following this exposure, contacts with interested staff from Sandia National Laboratories (particularly Don Shuster) and the Air Force Space Systems Division (with the help of Lew Allen) led to a joint seminar. The seminar produced proposals for experiments, which would be mounted and flown on sounding rockets available at the time. Because nuclear weapons had already been exploded in "near space," a question arose as to whether or not such explosions could be detected far away from Earth. This arises because the visible light emitted directly from an explosion is a very small fraction of the weapon's total energy, and no other interactions occur with the atmosphere at great distances. Obviously, instrumented satellites would have a much better chance of detecting clandestine explosions if they were located well outside of the atmosphere. A joint Advanced Research Projects Agency and AEC program was started in 1962 to look at the options available. In addition to the Los Alamos/Sandia cooperation, Lawrence Livermore National Laboratory and the Aerospace Corporation participated in the discussions. After a lengthy analysis, the Los Alamos approach of using fully instrumented satellites for the detection mission with back-up instrumentation to greatly expand our basic understanding of the space-background environment was approved for the mission.

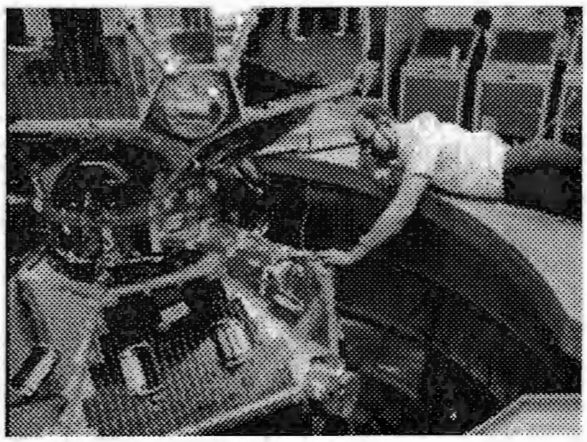
Interested staff members from Los Alamos were primarily the P-4 group from the CW accelerator and others from different parts of P Division. This staff was well acquainted with the methods used to detect neutrons, gamma rays, and x-rays and had rather quickly designed detectors for measuring the radiation. They also established the criteria for handling the data pulses and the transmission of information back to Earth. The Sandia group was fully versed in encoding detector pulses and in transmitting data back to Earth for reduction and analysis.

Scientists had already determined from the known background-radiation effects on the detectors that the satellites should orbit the Earth at approximately 100,000 km from the surface to have a sufficiently low background for data extraction. Thompson, Ramo, and Woolridge (TRW) would build the satellite structure; the Air Force Space Systems Division would perform the launch using Atlas Agena rockets.

The technical collaboration among Los Alamos, Sandia, and TRW was excellent. Accomplishing the scientific objective required a large number (thousands) of solid-state devices from Sandia for data acquisition and transmittal. This degree of complexity had not yet been accomplished in the United States space program at the time, and the predictions of the working lifetime of each satellite varied from a few seconds to a few days. Sandia therefore used severe testing methods to eliminate devices that did not meet the criteria, which had been established.

In this same year (1962), a nuclear-weapons-test program was carried out at high altitudes with rocket launches from Johnson Island. Many diagnostic measurements were performed on Starfish, a large thermonuclear weapon. Group P-4 proposed and carried out measurements that used a version of the neutron counter and circuitry from the satellite program to detect neutrons from the Starfish explosion at great distances. These measurements could not have been made unless neutron sources and detectors were well above the atmosphere. Thus, these detectors were launched on rockets from the Hawaiian Islands and from the California coast. The California rockets did not acquire data because of launch failure, but the Hawaiian detectors were able to measure the neutron time-of-flight spectrum from Starfish with a baseline of about 1,000 km.

The initial launch in October 1963 from Cape Canaveral put two of the Vela satellites into the prescribed orbit of 100,000 km. Considering the historically early launch time, these satellites were highly successful and immediately began to provide data on cosmic-ray backgrounds; solar flare; low-shock, magnetic-field measurements; electron and positive-ion populations; shock waves in the space plasma; and other phenomena. Above all, the reliability of the whole satellite system, especially the data-delivery capability, was fully tested and found satisfactory.



Dick Belian, on the gantry of the Vela satellites, inspects a cosmic x-ray detector.

Because the surveillance mission required a minimum of six satellites at the orbital altitude being used, the second pair was launched in July 1964 and the third in July 1965. All were successful and their lifetimes were fully compatible with the mission. Each satellite had 10 x-ray detectors for fractional to few keV

x-ray gamma-ray detectors to work in the hundred to few thousand keV, and 2 neutron counters sensitive for neutrons of energies of a few keV to 16 MeV. Detection capability of the x-ray system for a 1-Mt explosion was about 3 x 108 km, 3 x 106 for the gamma-ray system, and about 3 x 105 km for the neutron detectors—about one-quarter the distance to the moon.

During the long lifetime of the satellites, new information was discovered about the Sun's behavior and its effects on the space environment, but the most scientifically interesting observations were in the astrophysical regime. In reviewing old data tapes for short-lived events, scientists observed pulses in the gamma-ray detectors of a fractional second to a few seconds in duration, which were produced by gamma rays of energies in the hundreds of keV. Such hard gamma rays and other data clearly indicated a galactic origin, which in turn implied high total-energy content of the event. Although there are several tentative explanations for this phenomenon, no fully satisfactory hypothesis or theory exists to date.

The original observations were made by Ray Klebesadel, and since that time, research has also been done by Ian Strong, Harold Argo, and Sam Bame. The design of the orbital distribution of the satellites for optimum surveillance produced corroborative support for observation by a single satellite. The pulse intensities at one side of the orbit and the directly opposite side were large enough to trigger both detectors, which were separated by about 3 x 105 km. Furthermore, there was a delayed coincidence between the two detectors, which indicated the general direction from which the gamma-ray pulse came!

Although the Vela program changed direction in recent years, its now enlarged responsibilities in the area of surveillance have made it a valuable program for national defense.

One cannot but be impressed by the obvious synergism apparent in the Vela program. The background of the staff in nuclear-radiation detection and measurement as applied to nuclear weapons explosions was necessary for design parameters in response to the different sizes and yields of weapons. The breadth of knowledge of the staff about astrophysics and space technology allowed for the quick and successful response to the mission requirements. The coupling of the basic research on space environment to the applied mission was anticipated as a necessary step. This all-important project might have failed without the final data provided through both basic research and applied science.

During the 1950s and 1960s, Los Alamos became an outstanding national center of scientific research and development and took its place among the very best of the famous international laboratories. P Division participated in this desirable development with an outstanding staff widely respected in academic circles, other United States laboratories, and scientific institutions in Canada and Europe.

I have attempted to identify the scientists who carried out the research that made Los Alamos famous. Unfortunately, the length of the article resulted in many omissions of which I am aware, both in subject matter and in acknowledgments. Therefore, I wish now to say that I recognize the contributions of most of the total scientific and technical support staff in P Division during the period in which I too was involved. I had help in putting together this report from many of the leaders of the programs and experiments, but errors and blunders of science

and substance are my own, and for these I apologize.

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