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Introduction

The Discovery of Spontaneous Fission in Plutonium

It was the spring of 1944. In a secluded canyon in New Mexico, 14 miles from the bustling technical area of the wartime Los Alamos Laboratory, three physics graduate students were working inside a Forest Service log cabin filled with electronics. For the past eight months, they had been driving there each day by jeep to search for evidence of "spontaneous fission," a naturally occurring process in which certain heavy atomic nuclei split of their own accord, emitting neutrons. Anxiously, they puzzled over a startling oscilloscope trace produced by a sample of plutonium. Why were these students studying the phenomenon of spontaneous fission in this canyon? What caused their concern?

The professor in charge of the work, nuclear physicist Emilio Segrè, had fled Italy in 1938 and joined Ernest Lawrence's nuclear physics laboratory in Berkeley, California. In 1943, at the request of theoretical physicist J. Robert Oppenheimer, Segrè had moved several of his Berkeley experiments to Los Alamos to be part of Project Y – the secret project to build the first atomic bombs. Jointly directed by Oppenheimer and military engineer Gen. Leslie R. Groves, Project Y was

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a part of the Manhattan Project (the Manhattan Engineer District). Before World War II, Los Alamos, a small New Mexico town on a high mesa, had been the site of a ranch school for boys. It was suddenly transformed in 1943 into a stark military community that included many of the world's best scientists.

The plutonium isotope of mass 239, ^{239}Pu, was one of two materials that Los Alamos planned to use in its atomic bombs. Both plutonium and the other material, the uranium isotope of mass 235, ^{235}U, fissioned readily when bombarded with neutrons, yielding further neutrons in sufficient numbers to sustain in principle an explosive chain reaction. In both cases, however bomb-size amounts of the fissionable material were difficult to amass. ^{235}U could be separated from natural uranium by a tedious, difficult physical process.[1] ^{239}Pu could be produced by bombarding the more abundant uranium isotope ^{238}U with neutrons, and then chemically separating the created plutonium. Since the density of neutrons needed to manufacture bomb-size quantities of ^{239}Pu occurred only in a nuclear reactor, Groves authorized the construction of several plutonium-generating reactors – a small pilot plant at Oak Ridge, Tennessee, and three production reactors at Hanford, Washington.[2] It took until April 1944 for these reactors to produce and send samples of plutonium to Los Alamos. In the preceding eight months, the physicists had had to make do exploring minute (microgram) plutonium samples prepared in cyclotrons, in the hope that the properties would match those of reactor-made plutonium.

Spontaneous fission was on the Los Alamos research program because the two fission bombs that were to be developed initially – "Little Boy" (uranium) and "Thin Man" (plutonium) – were of the "gun"-type design. In a gun weapon, one subcritical piece of fissionable material is shot into another, to form a supercritical mass that then explodes, yielding huge amounts of energy. The laboratory was optimistic about meeting its military objective – namely, to develop both bombs by summer 1945 (when Hanford was to begin producing sufficient amounts of plutonium for bombs) – because the problems associated with building gun weapons were extensions of familiar problems of nuclear physics and ballistics. However, Thin Man presented a number of difficult challenges. For one thing, the number of excess neutrons in the system had to be kept to an absolute minimum. Because gun assembly is a slow process in comparison with the speed of a nuclear explosion, extra neutrons threatened to set off the explosion too early and cause a "fizzle."

Two processes in plutonium could potentially spray extra neutrons into the system: impurity reactions and spontaneous fission. Hoping to minimize the number of neutrons resulting from interactions with impurities, the project managers set up large plutonium purification programs both at Los Alamos and at the Chicago Metallurgical Laboratory. At the same time, Oppenheimer authorized Segrè's spontaneous fission experiments to determine whether neutrons from spontaneous fission were worth worrying about. This authorization was but a precaution, for theory suggested that even if spontaneous fission occurred, the rate would not be high enough to threaten the plutonium gun. Indeed, when Segrè's group measured the rate of fission in cyclotron-made plutonium, they found it comfortably small.

The Segrè group chose to work in a canyon because the experiments were extremely sensitive to environmental disturbances. The level of data collected was extraordinarily low – less than one count per month! To keep background "noise" to a minimum, the group worked in conditions as free as possible of radiation, loud sounds, electrical surges, and other disturbances. All the equipment was battery operated.

Segrè's students were alarmed in mid-April 1944 because they measured in the first samples of reactor-made plutonium, a spontaneous fission rate *five times* that of the cyclotron-produced samples – a rate far too high for a gun assembly! Every count taken over the next four months confirmed these preliminary findings. By July 1944, Los Alamos had to accept the failure of Thin Man.

A crisis ensued. Groves, wanting to preserve the investment that had been made in plutonium production (hundreds of millions of dollars), ordered a plutonium bomb assembled by other means. The only possible alternative was implosion, an assembly explored thus far at Los Alamos only as a contingency. In such an assembly, a subcritical sphere of fissionable material is collapsed inward by the blast from a symmetrical array of high explosive. This process had the advantage of being so rapid that spontaneous fission neutrons would not have time to interfere with the explosion.[3] But those working on implosion in June 1944 thought it would be virtually impossible to achieve a practical implosion for use in the present war. As a result, Los Alamos was forced to turn its relatively small implosion program into a model "big science" effort involving hundreds of workers.

Resolving the Crisis: A New Approach to Research

This book tells the story of how the Los Alamos scientists responded to the spontaneous fission crisis they faced more than a year after the start of Project Y and how this response to the possible failure of the plutonium weapon motivated them to take a new approach to research that enabled building both of the first two atomic bombs. Los Alamos was able to complete the "Fat Man," as the plutonium implosion bomb came to be called, as well as the uranium gun, in time for combat use because Project Y was reorganized radically, and confronted its problems by a powerful methodology fostered by the wartime context.[4]

Under the new approach, members of the communities that coexisted in wartime Los Alamos – the scientists, engineers, and military personnel – blended their traditions. Such blending of scientific and engineering traditions had already begun (on a smaller scale) at Lawrence's laboratory in the 1930s and in a number of the science-based industries.[5] Under the conditions at Los Alamos, however, the process solidified. Historians are only just beginning to study the consequences for the postwar world – both positive and negative.[6]

Scientific research was an essential component of the new approach: the first atomic bombs could not have been built by engineers alone, for in no sense was developing these bombs an ordinary engineering task. Many gaps existed in the scientific knowledge needed to complete the bombs. Initially, no one knew whether an atomic weapon could be made. Furthermore, the necessary technology extended well beyond the "state of the art." Solving the technical problems required a heavy investment in basic research by top-level scientists trained to explore the unknown – scientists like Hans Bethe, Richard Feynman, Rudolf Peierls, Edward Teller, John von Neumann, Luis Alvarez, and George Kistiakowsky. To penetrate the scientific phenomena required a deep understanding of nuclear physics, chemistry, explosives, and hydrodynamics. Both theoreticians and experimentalists had to push their scientific tools far beyond their usual capabilities. For example, methods had to be developed to carry out numerical hydrodynamics calculations on a scale never bfore attempted, and experimentalists had to expand the sensitivity of their detectors into qualitatively new regimes.

As much as the scientists would have liked to provide technical solutions based on full understanding of fundamental laws, meeting Groves's deadline of building the atomic bombs by summer 1945 precluded traditional, methodical research and analysis. Moreover, the wartime prob-

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lems were necessarily tied to practical issues, like fitting bombs into the B-29 bomb bay or building components that could withstand the severe conditions of high-altitude drops. However "pure" the scientists wanted their work to be, they were forced by the wartime circumstances to embrace the methodology of Edison.[7] That is to say, their objectives shifted from understanding to use, and from general conceptions to particular materials and apparatuses.[8] This reorientation encouraged them to diversify their methodological toolkits with approaches typically employed by engineers and craftsmen, whose technical problems were anchored in concrete phenomena.

In view of the military application of their work, Los Alamos scientists were also forced to pay strict attention to reliability. Thus they sought alternative assemblies in their early efforts (such as the original implosion program or the thermonuclear bomb, at a time when the laboratory was emphasizing the gun method) and they subsequently overdesigned both the gun and implosion bombs in an attempt to guarantee success. The urgency of the wartime mission, the high cost and possible future accountability of research on the atomic bomb, the frightening consequences of miscalculation, the scientific and technological uncertainties of bomb design, the unusual availability of almost unlimited funding and other resources – all these factors fostered a conservative research strategy aimed at avoiding risk. One result was that multiple approaches were taken in addressing most of the problems.

This strategy paid off. For example, the relatively small-scale implosion studies conducted in the first year of Los Alamos yielded concepts that proved essential in completing the Fat Man (e.g., Alvarez's simultaneous electric detonators, Tuck's three-dimensional explosive lens for focusing shock waves, and Christy's brute-force core design). Most important, when the spontaneous fission crisis hit, the laboratory already had an organized research effort that could be shifted quickly to a crash implosion program. In the second year of the project the strategy of "overkill" continued as major attention focused on refining determinations of critical mass and exploring implosion. Typically, Los Alamos researchers sought the most dependable, rather than the most elegant, solutions.

The tight deadline scientists and engineers faced was a critical constraint. They managed to meet it – the entire Los Alamos project was completed in a scant twenty-seven months – in part because the organization of teams combined scientific practice with management procedures borrowed from industry. A strong mission orientation was im-

Fig. 1.1a. Robert Oppenheimer, theoretical physicist, first director of Los Alamos laboratory. LA Photo, 85 1780.

Fig. 1.1b. Major General Leslie Groves. Commanding General, Manhattan Engineer District. LA Photo, LAR 611.

posed: projects in line with the mission received essentially unlimited funding and material support, whereas others were dropped or starved (as was the thermonuclear bomb) of resources. Because the research at Los Alamos was in the national interest, strings were often pulled to supply high-priority projects with the needed equipment or personnel.

Oppenheimer did his best to ensure research freedom, but to meet deadlines he was forced to manage the program in quasi-military fashion. He was empowered to function like a general positioning his scientific troops. It was not uncommon for a researcher to be switched overnight from one project to another having higher priority. Leaders below Oppenheimer on the organization chart directed their groups with the same militarylike authority. Scientists, engineers, and technicians were expected to work together and communicate effectively, thus pooling their separate experience and knowledge about particular problems. Chemists and metallurgists, who rarely talked with each other before the war, found themselves working together in the same division.

Information flow was aided by many committees at the laboratory. Los Alamos was possibly one of the most introspective research organizations ever to exist. Group and division leaders assessed the work of their units in biweekly or monthly committee meetings, and division leaders participated in various advisory committees, such as the Governing Board and the Coordinating Council, which continually reported on progress and suggested the direction of future research. Numerous outside consultants, advisers, and committees also reviewed the work, often biweekly, making recommendations that the laboratory was obliged to take seriously.

This tightly organized, introspective hierarchical institution brought forth a new breed of scientific leader, one able to negotiate with committees, while managing much larger teams than had ever before existed in science. In the early phases of the implosion program, a practical academic scientist such as Seth Neddermeyer could cope with directing the implosion team of half a dozen scientists. But after August 1944, when some implosion teams included 50 to 100 researchers, the new implosion leaders had to be strong managers. Robert Bacher and George Kistiakowsky fit into this category.[9]

By the time Project Y was under way, the American physics community had matured sufficiently to handle the challenge of building the atomic bomb. It was no longer scientifically and institutionally backward in comparison with Europe. Although the group of approximately 200 practitioners of physics in the United States up to 1895 included such renowned scholars as Henry A. Rowland, Willard Gibbs, and Albert Michelson, the first American to win a Nobel Prize in physics, America's physicists were still too few and too widely dispersed to establish high general standards for research. Most lacked Ph.D.s and few published. American physics was then also without professional societies and journals to disseminate information. Industrial research, already established in Germany, was virtually nonexistent.[10] Nor was there an adequate institutional structure upon which to build a vital physics community; only six universities fully prepared students for graduate work in physics, and not all offered first-rate instruction. America's best physicists traveled to Europe for their education and published in European journals. Furthermore, American universities burdened physicists with large class loads. Finally, in an era that celebrated the useful and profitable, only a few philanthropists sponsored basic research projects. In government, only the Smithsonian Institution had a policy of promoting the pursuit of abstract knowledge, and its budget for such purposes was limited. The National Academy of Sciences (NAS), a private organization founded during the Civil War to advise the government, had little money or influence inside or outside the scientific community.[11]

In the last years of the nineteenth century, progress began to be made in the institutionalization of this area of American science. The American Association for the Advancement of Science established a physics section in 1882. In 1894 the *Physical Review* was published for the first time. Leaders of the physics community founded the American Physical Society in 1899.[12] Aided by growing philanthropic support from such wealthy patrons as Johns Hopkins, Jonas Gilman Clark, and John D. Rockefeller, Sr., graduate-level programs in physics expanded.

Growth continued after 1900 as new agencies, including the National Bureau of Standards and the Carnegie Foundation, funded research.[13] Recognizing that basic research had commercial value, large companies such as General Electric (GE), du Pont, and American Telephone and Telegraph (AT&T) established research laboratories sponsoring pure and applied research on a wide range of technologies, such as vacuum tubes, explosives, chemical dyes, artificial fibers, telephone transmission equipment, and X-ray and radio tubes. By 1930, almost 33,000 scientists and technicians were employed in industrial research laboratories. Industrial laboratories tended to emphasize teamwork.[14]

The privately funded National Research Council (NRC) brought together top scientists and engineers from academia, industry, and government to promote military research. During World War I, astronomer George Ellery Hale promoted, organized, and managed this council under the auspices of the NAS. Although the NRC's influence with the military decreased markedly after the armistice, wartime accomplishments, including the development of submarine-detection equipment and aeronautical instruments, convinced military and government leaders that science could have defense value. Strengthened ties between the physics community and industry further stimulated the employment of physicists in industry.[15]

American physics continued to prosper throughout the 1920s and 1930s, despite the Depression.[16] Advances in quantum theory stimulated interest in the microscopic structure of matter, and in 1923 Robert Millikan of Caltech was awarded the Nobel Prize for his work on electrons. In the 1930s and 1940s, Oppenheimer taught quantum theory to large numbers of students at the Berkeley campus of the University of California as well as at Caltech. Also at Berkeley in the 1930s and 1940s, the entrepreneurial Lawrence gathered chemists, engineers, and physicists together in a laboratory where he built a series of ever-larger cyclotrons and led numerous projects in nuclear chemistry, nuclear physics, and medicine. By bringing together specialists from different fields to work cooperatively on large common projects, Lawrence helped to create a distinctly American collaborative research endeavor – centered on teams, as in the industrial research laboratories, but oriented toward basic studies without immediate application.[17] This approach flourished during World War II.[18]

Ties between the physics community and the government strengthened during the 1930s. The Science Advisory Board was established in 1933 at the instigation of Karl Compton, president of the Massachussets Institute of Technology (MIT). Although attempts to renew the board's charter failed in 1935 in the midst of antagonisms between scientists and politicians, the board stimulated federal funding of scientific projects and gave leaders like Compton, Millikan, and Vannevar Bush political experience and contact with important members of the Roosevelt administration.[19] Such scientific leaders, whose talents spanned science, engineering, and management, were brought forward by the wartime projects.

As political troubles loomed in Europe, American physics reaped benefit from tragedy. Between 1933 and 1941 more than 100 physicists, mostly Jews from Germany and Austria, fled to the United States to escape Hitler and Mussolini. American laboratories, now capable of providing both economic security and a stimulating intellectual environment, attracted such people as Enrico Fermi, Hans Bethe, John von Neumann, Edward Teller, and Eugene Wigner. These immigrant scientists made important contributions to American science and helped to complete its maturation.[20]

As this book argues, the factors operating in wartime Los Alamos – the pragmatic mission of the laboratory, its ample financial support, strict time pressure, and the imposed risk-averse policy – in combination gave rise to an empirical problem-solving methodology based on systematic trial and error rather than thorough analysis. Traditional analytic methods were simply too slow. Among the particular techniques that the Los Alamos physicists and chemists used frequently, in combination with more traditional scientific ones, were the *Edison approach* of trying, in the absence of good theoretical guidance, one after another system or material; the *shotgun* approach, in which all experimental techniques available and everything known about a particular issue were fired at the problem to be solved, in hopes that one or more techniques would hit on a piece of the problem and reveal some important facet; *overlapping approaches*, in which multiple approaches were taken simultaneously to a specific problem in recognition that any one could be incomplete and uncertain by itself, but that together they might be used to build up a consistent picture; the *small-scale model* study, to save time and precious materials; *iteration*, the systematic generalization of cut-and-try "tinkering," long characteristic of American science,[21] in which empirical models were progressively improved after testing; and *numerical analysis*, now for the first time extensively done by computing machines. Although messy and unaesthetic, numerical methods were more far-reaching than analytical models alone, which were simply too incomplete and idealized to handle concrete problems. However, when combined with analytic methods, numerical ones formed a tool of striking power.

To illustrate, the Edison approach guided the countless implosion shots fired. The shotgun technique was combined with overlapping approaches in the many-stranded implosion diagnostic program, in which seven complementary types of experiments – X-ray, photographic, terminal observations of implosion remains, magnetic, electric "pin," betatron, and the "RaLa" method – were oriented toward gathering a flood of data on implosion. Scale models were used in every implosion diagnostic exercise. Iteration was used extensively in the explosive lens program because explosives exhibited complex phenomena and had been little studied previously. In building lenses, theorists would make educated guesses of the index of refraction, on the basis of which the lenses were cast with approximately correct geometries. Their actual index of refraction and focusing properties were then determined and used by the theorists to improve their guesses for the next iteration toward good experimental lenses. Similarly, the development of detonators required trial and error and redundancy, because there was no other way to meet the deadlines reliably. Numerical methods, carried out with the help of IBM calculators (International Business Machines), were employed extensively in the implosion program. The brute-force Christy design simply circumvented the serious symmetry and stability problems of a more elegant implosion design.

The special conditions that nurtured the new approach could continue only under the wartime pressures to build the atomic bomb. Although quite a few members of the original Los Alamos scientific community remained at the laboratory after the war to complete the unfinished work or to take part in the new science that splitting the nucleus had just