NATIONAL ACADEMY OF SCIENCES

JESSE W. M. DUMOND

1892—1976

A Biographical Memoir by

W. K. H. PANOFSKY

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July 11, 1892–December 4, 1976

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JESSE W. M. DuMOND died December 4, 1976, after a career characterized by extraordinary length and productivity. Jesse DuMond was a physicist, with that term encompassing all branches of the science. He was an experimental designer with extraordinary gifts, a skilled experimenter and an inspired interpreter of results, and a correlator of data gathered by others. He was, above everything else, driven by his notion of the inseparability of all phases of his work and by the wholeness of all physics. In order to have full confidence in the results obtained, he would delegate any component of his work to others only under extreme duress. For this reason, each item of apparatus, each calculation, and each interpretation was, wherever possible, a product of his own hand and brain.

Jesse DuMond was the most inspired mechanical designer I have ever known. He had an infallible sense of geometry, and he would prefer geometrical analysis and construction to any analytical or numerical method. His best-known work is his discovery of the broadening and fine structure of Compton scattering of X-ray photons. This work, born in some controversy, gave persuasive evidence of the dynamic nature of the Bohr atom by demonstrating the motion of orbital electrons.

Let me elaborate this glimpse of DuMond's contributions and work by outlining his career in more detail. Happily, in November 1972 DuMond had completed, under the far-sighted sponsorship of the American Institute of Physics, a two-volume work entitled *The Autobiography of a Physicist,* to which the reader is referred for greater detail and for a poetic description of DuMond's career in his own words.

Jesse DuMond married Irene Gaebel in Paris in 1920. They had three children, two of whom married; they are (Mrs.) Desiree Andre Wilson, born in 1927 and (Mrs.) Adele Irene Panofsky, born in 1923. DuMond remarried in 1942 and is survived by his widow, Louise DuMond, as well as by eleven grandchildren.

EARLY EDUCATION AND MILITARY SERVICE

Jesse DuMond was born July 11, 1892 in France, of American parents. His mother died while he was an infant, and his father and his uncle were both artists of some renown. Interestingly, his early childhood reflects an attraction both to technical and artistic influences. He was brought up in the care of a maternal grandmother and great-aunt, but when his father remarried, his education and upbringing became the responsibility of his paternal grandfather, residing in Rochester, New York, and later in Monrovia, California. He went to high school in Monrovia and at the same time received a thorough exposure to the mechanical arts through his grandfather. DuMond's grandfather was a very unusual person. He was a self-educated man who had been a sailor and had engaged in various trades. He then decided to settle down and start a sheet-metal business. Despite, or possibly because of, his lack of a formal education, he had a deep respect for books, for poetry, and for learning in general, and at the same time had the highest standards of craftsmanship. Under his tutelage, DuMond acquired his deep understanding of geometrical and mechanical principles and the skills in mechanical design that were to serve him so well during his later scientific career.

DuMond's grandfather had a negative attitude about art as a career. Thus DuMond's dual interests, in art, and science and the mechanical arts, reflect his dual upbringing by his father and grandfather.

After completing schooling in Monrovia, DuMond held a number of jobs and then entered, in 1912, what was then known as Throop College, later to become the California Institute of Technology. At that time Cal Tech was not as yet a full-fledged graduate institution offering the Ph.D. degree, nor had it collected many prominent research people. Moreover, its president, the famous astronomer George Ellery Hale, felt that Throop College should produce not just engineers and scientists, but should offer a well-rounded education. It is characteristic that this task of balancing the technical education with some instruction in the humanities fell to a single professor, Clinton K. Judy, who apparently had a large influence on DuMond's increasing interest in poetry and the arts, in addition to his growth in physics and engineering.

DuMond completed his undergraduate education in 1916 with an excellent record, receiving several prizes. His thesis consisted of the construction of an harmonic analyzer, which at that time was considered to be a highly advanced calculating device. After receiving his undergraduate degree, DuMond took a job as a test man at General Electric in Schenectady, New York and continued part-time study at Union College. He had some contact with the famous C. P. Steinmetz, then considered to be the leading genius in electrical engineering. Steinmetz's extensive use of complex variable analysis of alternating current circuits inspired DuMond to design and construct a complex quantity slide rule, in essence a very ingenious, two-dimensional plotting table, which I had the privilege of using. Again, this development, which became his master's thesis, was indicative of DuMond's preference for using geometry rather than algebra whenever possible in the solution of difficult problems.

Apparently, after initial enthusiasm, DuMond considered his work at General Electric to be unpromising, too routine, and leading only to administrative or organizational positions. Accordingly, despite the successful efforts by the General Electric Company to defer DuMond from military service, he enlisted in the army and became a member of a sound-ranging battalion in France. In those days locating enemy batteries by sound ranging was far from a routine operation. In command of the army's sound-ranging effort was Professor Lyman of Harvard University, who attained the rank of colonel in this profession. Sound ranging by the enlisted men involved learning to distinguish the sound waves from the muzzle blasts of guns, which propagated at the ordinary velocity of sound, from the ballistic shock waves of the projectiles' flight, which did not. The whole technique of sound ranging was developed by Sir William Bragg of England. In short, sound ranging during World War I involved the leaders of U.S. and British physics. As a sound ranger DuMond served on the front under fire, but was never involved in personal combat.

POSTWAR EMPLOYMENT AND GRADUATE STUDY

The Armistice led to orders for DuMond to be honorably discharged back in the United States, but he attempted to stay in France to settle the estate of his recently deceased grandmother who had been responsible for his early upbringing. Combining his stay in France with discharge from the army proved to be impossible; thus after continuing various minor technical jobs for the Army, DuMond found it necessary to make a round trip to San Francisco to be discharged and then returned to Paris to settle the estate. To make this trip and stay in France feasible economically, DuMond decided to take a position with the Thomsen-Houston Company in France, which at the same time had reached an agreement with General Electric to standardize the design of large turbine generators to be marketed in Europe and the United States. DuMond's job consisted of translating the G.E. designs, down to the detailed blueprints, into a form suitable for production by French methods. Although this was a relatively routine task, it contributed substantially to his deep understanding of the detailed problems faced in engineering and production.

After this engineering interlude, caused primarily by the vicissitudes of U.S. military and French judicial bureaucracies, DuMond resumed his scientific career, first in a position with the National Bureau of Standards. He worked in a group headed by Harvey Curtis, who was at that time engaged in refining the determination of the absolute ampere by the classical current balance method. Although DuMond participated in this work in only a minor way, it kindled his lasting interest in work on precision determination of natural constants, and it impressed upon him the distinction between absolute units and those units established by standards of convenience.

DuMond's primary work at the Bureau was to assist Curtis in his work on the interior ballistics of guns. The work consisted of recording the recoil displacement of guns after firing as a function of time, and from this information computing the dynamics of firing. Again, this work, although relatively routine in nature, introduced DuMond to the intricacies of data analysis and curve fitting, using the relatively primitive techniques of those days.

In 1920 the National Bureau of Standards was a prime intellectual center in American physics. Visiting lecturers included the pioneers in atomic and quantum theory, and there was extensive discussion concerning the validity of the special theory of relativity. The atmosphere was congenial and led to much intellectual stimulation. Induced by this experience, together with the modest amount of money inherited by the settlement of his French estate, DuMond decided that more advanced education was a necessity for a career in physics. He therefore applied to Cal Tech to work towards a Ph.D. degree, and he was admitted in 1921.

DuMond's period of graduate study was a long one, leading to a Ph.D. degree in 1929 just short of his thirty-seventh birthday. His studies towards the Ph.D. were interrupted by two trips to France. Also, his field of investigation—X-rays—was one of his own choosing and not carried out under direct supervision of a more experienced member of the faculty. However, his thesis, dealing with the broadening of the Compton effect due to the internal motion of electrons in an atom, describes one of the truly classical experiments in atomic physics.

STUDIES OF THE MODIFIED COMPTON LINE THE DYNAMICS OF THE ATOM

DuMond was acquainted with the discovery of the Compton effect. He recognized, however, that the usual derivation of the Compton shift assumed that the electron struck by the incident photon was at rest, and that therefore broadening of the Compton-scattered line should result if motion of the electron was taken into account. Accordingly, DuMond proposed detailed study of the modification of the Compton-scattered line as a valuable tool in studying the velocity distribution of electrons in atoms. Recently Richard Feynmann and Richard Wilson have given eloquent credit to DuMond's recognition of this fundamental fact. DuMond's measurements were accompanied by an extensive set of papers relating theoretically the shifted line shapes to the atomic electron motion.

DuMond's studies of the broadening effect of electron motion on the Compton line were beset both by technical and human difficulties. Intensities available from X-rays combined with X-ray spectrometry with single crystals gave insufficient intensity. DuMond's studies in classical optics made him aware of the properties of the Rowland circle, which had been in use for a long time in optical spectroscopy. He immediately realized that if a crystal operating in accordance with the Bragg reflection condition was to serve as the grating in the conventional Rowland configuration, then the radii determined by the focusing conditions and the Bragg reflection condition were incompatible by a factor of two. Starting from this conflict, he proposed that these two radii could indeed be independently created by either configuring a large set of independent small crystals along one of the radii while orienting each crystal along the other, or by bending a crystal so that the crystal planes would conform to the Bragg condition. While publishing both of these solutions, DuMond rejected the second one as impractical to the accuracy required and embarked on the construction of a multi-crystal spectrometer. At the same time other workers in Europe, notably H. H. Johann and Y. Cauchois, used DuMond's suggestions as a point of departure for the construction of curved crystal spectrometers. DuMond complained throughout his career that the priority of his proposal of the curved crystal spectrometer had never been adequately recognized by those who first reduced it to practice.

Using a spectrometer constructed with fifty separate crystals, DuMond, with Harry A. Kirkpatrick, then investigated what has since become a milestone in classical atomic physics: He measured the broadening of the Compton line and extended this work to a number of elements. Although credit for this work is being accorded to DuMond universally, publication of these results was not without controversy. In particular DuMond accuses, and I believe with considerable merit, A. H. Compton himself of particularly ungenerous conduct in connection with these discoveries. The chapter of the classical text on X-rays, "Compton and Allison," initially reproduced DuMond's data without discussing their significance. Moreover, in subsequent critical discussions of the shape and position of the Compton-scattered line, A. H. Compton gave a great deal of credence to the work of a student of his, Gingrich, which subsequently was almost certainly proven to be incorrect. The work of Gingrich used a much less "luminous" two-crystal spectrometer. DuMond and an associate (A. Hoyt) did a two-crystal spectrometer experiment also, obtaining results in disagreement with Gingrich.

In view of the above events, DuMond found himself embattled in a rather unproductive controversy about priorities and credibility of experiments. In retrospect, there is little question that DuMond's period of graduate study at Cal Tech encompassed two exceedingly fundamental contributions: the discovery of the focusing properties of curved crystal or multi-crystal assemblies for X-ray spectroscopy, and the discovery, initial exploration, and theoretical interpretation of the modified Compton-shifted X-ray spectroscopy.

X-RAY STUDIES ON NATURAL ATOMIC CONSTANTS

I mentioned previously that DuMond returned to graduate study at Cal Tech inspired by the revolutionary developments in atomic physics of the early 1920's as introduced to him at the National Bureau of Standards, and that he felt he could return to such studies because of his small independent income. It was characteristic of DuMond's general attitude in those days that he relinquished a paid teaching assistantship at Cal Tech in order to make these funds available to other, presumably younger, graduate students who had no other means of support. This history was to repeat itself after his Ph.D., in 1929, when Cal Tech was in a state of financial crisis. R. A. Millikan, as head of Cal Tech, was deeply impressed by DuMond's contributions as a student and offered him the position of research fellow at Cal Tech to continue his work—without salary. DuMond accepted. In 1931 DuMond was offered an associate professorship at Stanford University. He worked and taught there for three months to become acquainted, and he made many friendships that endured into later years, in particular with W. W. Hansen whom he greatly admired. However, despite the obvious professional attractiveness of the position at Stanford—and the fact that it involved a salary—he decided to return to Cal Tech to continue his research. DuMond felt that the intellectual opportunities at Cal Tech during that time were superior to those at Stanford, and he particularly admired Millikan's leadership in attracting inspiring leaders in physics. Not until 1938 did DuMond receive a salary as an associate professor!

In those days obtaining some financial support to carry out experimental research was no mean accomplishment. R. A. Millikan tried to be as helpful as he possibly could in furthering the work of the members of the Institute. Specifically, Millikan succeeded in interesting an ever-widening group of industrial and professional leaders in the work of Cal Tech, and he introduced DuMond to a Dr. Leon L. Watters, a wealthy businessman from New York. This contact led to a gift* by Watters in 1933 in support of DuMond's work, which greatly amplified DuMond's ability to carry out his fundamental work on X-rays and natural constants.

* $9,000 total—a princely sum for research at the time.

Although the Watters gift appears modest by current standards, it provided DuMond the means to engage in what in those days was surely considered by some to be "big physics." Quite apart from the then higher value of the dollar, the leverage of such funds was enormous. The work in which DuMond engaged was largely based on ingenious design and painstaking construction of extraordinary apparatus. He generally carried out the work by himself, assisted by a dedicated group of students, associates, and gifted mechanicians. Only outside purchases had to be covered by the Watters grant.

Within this pattern, DuMond proceeded to construct two major installations. One was a 300 kw X-ray tube operating at voltages up to 100 kv. The tube was entirely laboratory built using surplus transformer bushings as insulators; many other "scrounged" components constituted the power supply and ancillary apparatus. Some purchased components were incorporated in the power supply, which had to be carefully regulated for the research to be undertaken. The X-ray tube incorporated a gyrating anode, a major innovation in those days. DuMond devoted extraordinary mathematical efforts to the quantitative heat conduction design of this anode, and he also designed and built the entire vacuum system. An interesting note is that DuMond decided to avoid the use of the then conventional McLeod vacuum gauges and instead designed and built a set of Knudsen gauges, which utilize the momentum of thermal bombardment of residual gas molecules to deflect a suspended vane. It was DuMond's habit to personally draw each component and assembly to the highest standards of engineering draftsmanship, and also to prepare perspective drawings for publication, since he felt that they communicated technical content better than photographs. It is interesting to note as a sideline that when he published the meticulous description of the Knudsen gauges there was much demand from others who wished to use but not to build them. Accordingly DuMond, in cooperation with one of the superb mechanicians in the Cal Tech shops, marketed this gauge for a while and received sufficient returns to pay for a summer vacation!

In addition to the high-powered X-ray tube, which represented a large advance in equipment available at the time, DuMond, together with an engineering student (Douglas Marlowe), designed and built a precision two-crystal spectrometer, which made it possible to position large calcite and other crystals to a precision of a fraction of a second of arc. Again drawings were prepared to meticulous standards and many highly ingenious innovations were incorporated to reach the desired precision at low cost. One of the innovations in which DuMond took great pride was the driving mechanism that rotated the crystals. This consisted of precision-lapped driving screws which drove large worm wheels. These wheels were split into two halves, and a spring between the two halves prevented backlash. This concept was not new, but DuMond supplemented it with a mathematically elaborate systematic lapping scheme. The teeth of the worm wheels were lapped with the two halves of the wheel superimposed on one another in what he analyzed to be the optimum sequence to average out the initial machining errors. This instrument was a success; again requests were received from several laboratories to make precise copies, since the kind of design skill incorporated in the small physics group under DuMond just did not exist anywhere else in the world.

Armed with this advanced instrumentation and other less unusual pieces of equipment, DuMond and his students embarked on a series of X-ray experiments dedicated to advance the frontiers of knowledge on the fundamental atomic constants—Planck's constant and the charge and mass of the electron. The foremost discrepancy among the atomic constants at the time dealt with the value of the electronic charge. For over two decades the measurements published by Millikan in 1917 were accepted essentially uncritically. However, the indirect approach to measuring the electronic charge by measuring the absolute value of the lattice spacing of crystals using X-rays of wavelength determined by grating reflection resulted in an uncomfortable discrepancy of almost 1 percent. To derive the electronic charge from the lattice-spacing measurements one needs to know the density of that part of the crystal contributing to the reflection of X-rays, as well as auxiliary constants such as the Faraday. A possible alibi for the discrepancy was, therefore, that those few atomic planes that participate in Bragg reflection in crystals might have an anomalous density—and one of DuMond's colleagues (Zwicky) proposed an elaborate theory of possible crystal superstructures that might be responsible. To investigate this proposed explanation, DuMond undertook two programs. One was to substitute transmission rather than surface-reflection measurement of X-rays to determine crystal-lattice spacings, thereby sampling the crystal in depth. The other was to obtain X-ray crystal diffraction patterns from powdered crystals (the Debye-Scherrer method), thereby taking a random sample of surface reflections. The first approach in particular turned out to be more difficult than anticipated, but through painstaking effort in a series of experiments DuMond and his students succeeded in bringing both methods to fruition. The result agreed well with the original surface-reflection data, thus contradicting the explanation that crystal non-homogeneities were somehow responsible for the discrepancy between the Millikan oil-drop value of the electronic charge and the X-ray diffraction value. It was these results, together with the persuasive communications to Millikan by Professor R. T. Birge of the University of California at Berkeley, who was then the most highly respected reviewer of natural constants, that persuaded Millikan to reexamine all the assumptions of the auxiliary constants used in his old oil-drop determinations. As is now well known, this review led Millikan to question the correctness of the value of the viscosity of air that he had used in the old experiments, and he put a graduate student to work to remeasure this parameter. This remeasurement successfully removed the discrepancy, and the X-ray measurements proved to be correct.

The second major application of X-rays to natural constants initiated by DuMond dealt with the ratio of Planck's constant to the electronic charge. This number can be inferred through a precision determination of the voltage threshold at which X-rays of known wavelengths are produced by electron bombardment. Such a measurement requires precision measurement of the X-ray tube voltage, precision wavelength measurement of the X-rays, and enough intensity to permit measurement at very high resolution of all these quantities. A measurement was carried out by DuMond and one of his students (Bollmann) before the Watters apparatus was constructed. Some uncomfortable discrepancies remained in the consistency of these measurements with the charge of the electron, optical measurements of the Rydberg constant, and measurements of the charge to mass ratio of the electron by various methods. Accordingly DuMond and his associates and students (including myself) engaged in a series of measurements that brought the power of the new instruments to bear on this problem. The result set a new mark in accuracy of determination of the so-called shortwave limit of X-ray production. It turned out that at the precision in question (a few parts in 10,000 in those days), considerable attention had to be paid to solid-state phenomena governing the details of the final state which the electron can occupy after emission of the X-rays near threshold, to the surface cleanliness of the anode, and to precise analysis of the factors determining resolution.

This work led DuMond to engage independently from, but in good communication with, R. T. Birge in a critical analysis of the worldwide picture of the natural constants. In those days DuMond strongly emphasized his disdain for numerical and, to some extent, formal statistical methods, and superimposed his dominant interest in geometry. He devised the so-called "isometric consistency chart" in which the combinations of values of the electronic charge and mass and of Planck's constant as contained in each particular measurement were represented by straight lines accompanied by parallel lines representing the probable errors. The success or failure of these lines to intersect in a small region represented the consistency or lack thereof of the multitude of measurements. In subsequent years DuMond was to publish successive literature and experimental surveys of the atomic constants, plotting his findings in such a chart. As complexity and precision of experimental determination of the natural constants increased, DuMond found it progressively more difficult to deal with these questions alone and formed an association with E. Richard Cohen, with whom he collaborated on critical evaluations of the natural constants for the balance of his life. Cohen, as a member of the younger generation, brought a thorough knowledge of computational methods to supplement DuMond's geometrical intuition and detailed knowledge of experimental apparatus. The successive reviews of DuMond and Cohen of natural constants became standard references on the subject for a protracted period of time.

THE BEGINNING OF GAMMA-RAY SPECTROSCOPY

The Watters apparatus had made it possible for DuMond to extend the traditional methods of X-ray crystal spectroscopy to higher energies. Motivated by this success, and draw-ing on his earlier invention of the curved crystal spectrometer, DuMond embarked on the new direction of gamma-ray spectroscopy. Following a suggestion by Y. Cauchois, he found that the spacings of certain crystal planes in quartz were sufficiently narrow, and their structure functions for X-ray reflections sufficiently large, that there might be hope of success. Accordingly DuMond designed a large (two-meter radius) and elaborate curved crystal gamma-ray spectrometer. This instrument posed several formidable design problems stemming from the small magnitude of the Bragg angle at gamma-ray energies. DuMond realized that a principal problem was precision collimation to separate the very weak Bragg-reflected beam from the direct beam from the source, and that therefore the collimator and detector would be very massive devices, while the source, being simply a radioactive sample, could be relatively small. DuMond designed an instrument in which the traditional Rowland circle geometry was reversed; the detector is stationary, while the source moves along the circle. Based on this principle, DuMond devised an ingenious kinematic arrangement controlled by a precision feed screw, which moved a curved crystal holder and a radioactive source in the correct kinematic conditions designed to preserve both the Bragg angle and the relevant focusing conditions. An additional feature of his kinematic solution to this problem was that the scale of wavelengths bore a linear relationship to the feed screw setting controlling the device. DuMond, in his autobiography, considered this design to be the best among his instrumental achievements.

Design and fabrication of this instrument under DeMond's direction, again executed by the superb mechanicians in the Cal Tech shops, was well along when World War II started. Final assembly and commissioning of the instrument was delayed by almost a decade since higher priority items were placed in the machine shops, and DuMond himself went on a leave of absence to the East to engage in military work.

As it turned out, this delay was a very fortunate one indeed. It is doubtful that the intensity of the radioactive sources available before the war would have been adequate to carry out experiments that would have made significant contributions to gamma-ray nuclear spectroscopy. The advent of nuclear reactors made it possible to activate large varieties of substances to yield nuclear gamma-ray transitions of intensities unprecedented before the war. This fortuitous circumstance made DuMond's gamma-ray spectrometer an enormously productive instrument.

This new instrument led to a shift from DuMond's prewar research activities with X-rays below 100 KeV to his postwar activities dedicated primarily to nuclear spectroscopy. This latter field was not DuMond's primary area of expertise. Therefore the choice of research topics to which DuMond's high-precision X-ray spectroscopic methods were to be dedicated in the field of nuclear spectroscopy were largely left to others. It was the fortunate combination of highly experienced nuclear spectroscopists and DuMond's extraordinary gift of instrumental design that shaped the postwar research period. However, let me first turn back to DuMond's contribution to military work during the war.

CONTRIBUTION DURING WORLD WAR II

DuMond's war work did not follow the mainstream of participation of most American high energy physicists. DuMond's personal style was very individual. He insisted on very high standards and, when recognizing that he could do a certain job himself more ably than delegating it to associates, he generally preferred the former course. DuMond's style did not lend itself well to participation in the mass assault on the pressing technical military problems of World War II to which physicists have contributed so much—radar, the atomic bomb, and the development of rocketry.

DuMond's first wartime activity took him to the East. There he worked at the request of the Bell Telephone Labs on a problem relating to degaussing the magnetic field of ships so that they would not trigger enemy magnetic mines. He did a great deal of work on mathematical solutions of the degaussing problem by synthesizing the magnetic field of coils to cancel successively higher moments. Based on these calculations, he constructed a simulator for modeling the magnetic field of ships and compensating that field on a moment-by-moment basis.

As his next assignment, DuMond became associated with the rocket propellant activities at Indian Head near Silver Spring, Maryland. There he worked on processes to extrude what is known as rocket "grain," resulting in a product which would burn in a rocket motor at controlled rate and thrust. He designed what was possibly the first successful extrusion press for solid rocket fuel, and his work became incorporated into basic rocket technology.

DuMond then returned to Cal Tech in December 1941. In continuation of his work on rocket technology, he initially associated himself with the large-scale rocket work then conducted at Cal Tech under the direction of Professor Charles C. Lauritsen. At the same time DuMond set up a small project shop in another part of the Institute to pursue more specialized projects that utilized his unique design skills more specifically. Although he made some useful contributions, such as designing some new types of rocket launchers, his association with the big rocket project at Cal Tech was only partially successful. The reason was not that his technical and personal qualities were not appreciated by all—on the contrary, everyone spoke with admiration of DuMond's skill and ability—but that his working methods and insistence on personal control did not lend themselves to the world of compromises inherent in the execution of a large-scale project of this kind. He therefore concentrated his work more and more away from the central tasks of the rocket activities at Cal Tech and worked on smaller projects. One of these was the design and construction of a large aerial camera for intelligence collection. This device used Schmidt optics configured to result in very high photographic speed. This camera was mounted on a set of gimbals arranged to rock in such a manner as to compensate for the ground speed of the airplane, thus producing a stationary image. The device worked excellently at unprecedented optical speed and resolution, but to the best of my knowledge, it never reached production or regular military use because no follow-up to make this instrument producible was provided.

DuMond's contact with the rocket activities led him to what was to become his major wartime contribution. He participated in a field exercise in northern California where rockets were used as targets for ground-to-air antiaircraft gunnery exercises. He recognized that the principal problem in using target rockets, or as far as that goes, targets of any kind, as training tools for antiaircraft fire was error assessment. Since actual hits were only obtained in exceptional cases, no evaluation of training effectiveness or improvement in performance could be made. DuMond, together with his associate A. E. S. Green, proposed that a remote sensor be mounted on aerial targets, which by telemetry could broadcast the distance between the projectile and the target.

The first concept developed by DuMond and his associates to achieve this was the use of magnetic detection. Large configurations of magnetic coils were designed, contrived to cancel magnetic disturbance from external sources, but sensitive to the magnetic field from hardened steel armor piercing, and magnetized, ammunition. This attempt was basically unsuccessful, since the attainable sensitivity did not meet the objective of detecting bullets at relatively large miss distances from the target. However, DuMond proposed an alternate approach, derived from his observation of the "crack" of bullets traveling overhead associated with his early experiences as a sound ranger in military service in World War I. He proposed that the shock wave of supersonic projectiles be the handle for measuring the miss distance of such projectiles from aerial targets. This initiative led to a more substantial project dedicated to developing practical detectors that could be mounted on airborne tow-targets, on target drones, or target rockets. Development of this device, called the Firing Error Indicator (FEI), took well over a year, but field tests were very encouraging. For the first time, firing crews who were encamped in the desert areas of southern California to practice shooting at aerial targets had information whether their performance improved as a result of such training. The device was placed into commercial production, but the products did not see much service before the end of the war. One problem was that the increasing speed of aircraft led to what amounts to technological obsolescence of this device. Based on observation of the acoustic shock wave, the FEI would become very inaccurate as the target fired at approaches the speed of sound.

Concomitant with the actual development of this device, DuMond delved more deeply into the theory of shock-wave propagation. With his associates, he wrote a much-quoted paper that derived theoretically the acoustic wave shape of high-speed projectiles and the modification of this wave shape as it propagates. Also, some of the techniques in producing and testing the ultra-precision microphones required for acoustical detection of shock waves led to important technological advances in that field.

There was one interesting sideline connected with this work, apart from its own intrinsic significance. Luis W. Alvarez, then at Los Alamos, had been assigned the task of designing sensors to be used both during the initial test of nuclear explosives and during their actual operational use in order to measure their yield. He decided that observation of the acoustic shock wave of the explosions was what was needed. Upon reading the results of the work of DuMond and associates at Cal Tech, Alvarez decided that his problem was essentially solved, and that the Firing Error Indicator would easily be adaptable as a shock-wave detector for nuclear explosions. Accordingly, secret liaison arrangements were set up between DuMond's project at Cal Tech and Los Alamos. The relatively minor modifications of the firing indicator for this novel use were carried out, and a special receiver to display the frequency-modulated signals was designed and built. Such a receiving unit was intalled in a B-29 that overflew the first nuclear explosion in Alamagordo, but the FEI devices were never dropped due to bad weather conditions. However, the devices were actually used during the nuclear bombings of August sixth and ninth, 1945 of Hiroshima and Nagasaki, and provided the primary information on the yields of the nuclear explosions detonated. There was a further sideline, as the shock-wave detectors were dropped by parachute at considerable distance from the explosion and therefore escaped destruction. Alvarez and associates at Berkeley used this fact to tape a message to the battery case of the shock-wave detectors, addressed to Japanese physicists, some of whom had worked at Berkeley. The record shows that this message was actually delivered to the addressees and by them to the Japanese high command. Thus a strange chain of development, beginning with DuMond's idea of using shock waves from bullets to assess errors during aerial gunner training, led ultimately to a means of communication during wartime to an enemy who may have had difficulty understanding what tragedy overtook him as a result of the development and use of nuclear weapons by the United States.

RETURN TO NUCLEAR SPECTROSCOPY

During the latter part of the wartime activities, DuMond and his associates found enough time to make small progress on the assembly of the gamma-ray spectrometer equipment. As the war ended, this instrument was ready for use, and initial testing showed that, using radioactive isotopes produced in reactors, gamma-ray lines could be measured with precision unprecedented in the history of nuclear spectroscopy. One of the first measurements dealt with the two-photon annihilation radiation of electrons and positrons. This measurement yields directly a value of the ratio of Planck's constant to the electron mass. Thus, even as DuMond's X-ray work moved into the MeV region, a link to the natural atomic constants remained. Wavelengths of gamma-rays from more than thirty nuclides measured to an accuracy of a few parts in ten thousand were published by DuMond and his collaborators in a remarkable series of papers from 1949 to 1963.

The postwar era in DuMond's work was shaped by the availability of this first gamma-ray spectrometer, which DuMond had designed and almost completed before the war. This instrument added new power to investigations of nuclear spectroscopy. Joining DuMond were numerous distinguished associates whose specialty was nuclear spectroscopy and who benefitted from DuMond's great gifts of instrumental design and construction. Among these were David Lind, Felix Boehm—who is now in charge of the heritage of DuMond's work at Cal Tech—and for some time Rudolf Mossbauer.

The instruments supporting the program of nuclear spectroscopy rapidly grew beyond the initial gamma-ray spectrometer. A further curved crystal spectrometer was constructed. In addition, it became clear that nuclear spectroscopy required beta-ray spectrometers also, and again DuMond's designs advanced the art considerably.

Triggered by the success of DuMond's first curved crystal spectrometers, which employed a 3″ × 4.5″ bent quartz crystal, demand increased from several institutions for DuMond to assist them in constructing similar instruments adapted to particular needs. An instrument using a quartz crystal of the unprecedented size of 11″ × 11″ was constructed for the Argonne National Laboratory in order to analyze gamma-ray transitions of extremely short-lived nuclides produced in a test reactor. Naturally, since this instrument had to be directly incorporated into the reactor configuration, the original concept of DuMond's first gamma-ray spectrometer could not be used because the kinematic solution he had adopted required motion of the source and not of the detector. The mechanical design of the Argonne instrument was done directly by the Argonne staff with DuMond acting as advisor.

David Lind, who had joined with DuMond to perform the first gamma-ray experiments after the war, starting in 1947, left Cal Tech in 1950 and worked for some time at the Nobel Institute in Stockholm. With the DuMond tradition being thus introduced into Sweden, an instrument was built at the Nobel Institute which permitted valuable cross-checks with the Cal Tech work.

To these variants of the initial design of a gamma-ray curved crystal spectrometer, DuMond and collaborators added another called the Mark III. It incorporated a large germanium crystal rather than a quartz crystal, since large germanium crystals are easier to obtain and bend. However, the degree of perfection so desired for such a crystal was more difficult to attain. The Mark III curved crystal spectrometer was more compact than the first design and had simpler kinematics. In particular the radiation source remained stationary. The design was so successful that it was copied by six institutions. A modified copy saw service at Livermore to analyze nuclear gamma-rays produced by the unprecedented intensity of the Livermore, so-called A-48, high-current deuteron accelerator, which was built as a model to demonstrate the feasibility of accelerator breeding of fissionable materials. This work was carried out as a result of a collaboration between DuMond and Hans Mark, then at Livermore.

Although as individual experiments the measurements of gamma-ray spectral lines as carried out by DuMond and collaborators may seem somewhat prosaic, their totality constituted a substantial fraction of the basis of the Nobel Prize award-winning proposal of Aage Bohr and Ben Mottelson on what is known as the collective model of the nucleus. Initial publications by Bohr, Mottelson, and associates relied heavily on the gamma-ray measurements made by the DuMond family of curved crystal spectrometers.

As mentioned above, the nuclear spectroscopists working with DuMond found it desirable to supplement the curved crystal gamma-ray spectrometer with beta-ray spectrometers also. There were two motives for this proposal: one was to provide a tool for beta-ray spectroscopy as such, and the other was to measure gamma-ray energies by observing the spectrum of Compton-scattered electrons in the forward direction.

To meet the first challenge, DuMond carried out a careful, systematic study of the optimization conditions that pertained to the design of beta-ray spectrographs of axial symmetry. Although many instruments of this general description had been built in the past, none of them was truly optimized to achieve the best compromise between luminosity, on the one hand, and energy resolution, on the other. DuMond showed that an optimum solution could be based on trajectories in a uniform magnetic field. If such a uniform field was used, DuMond showed that optimum luminosity for a given resolution would be obtained at a certain fixed cone of emission of electrons, and he showed that there existed a uniquely defined position for an annular slit to be mounted within the uniform magnetic field. Based on these fundamental considerations, DuMond designed an instrument in which the uniform magnetic field was produced by a set of coils placed on the surface of an ellipsoid, and where the entire apparatus was constructed of totally nonferrous materials. The required annular slit could be adjusted fully from the outside of the apparatus. The result was an incredibly complex design, and it speaks for DuMond's engineering genius that the apparatus was fully assembled from the parts as designed from his drawings without modification. Performance was exactly as predicted, and an important new tool was added to the arsenal of nuclear spectroscopists.

This instrument was not usable at the lowest energies of interest to beta-ray spectroscopists, and therefore one of DuMond's associates (Herbert Henrickson) designed a smaller matching instrument. In the time interval from 1951 to 1960 these instruments were the tools leading to analysis of the beta spectra of seventeen nuclides (incidentally, seven Ph.D. theses were produced). In addition to the instruments mentioned, a third spectrometer was built which was to serve the dual purpose of Compton electron spectroscopy and beta-ray spectroscopy. This instrument followed the classical solution of Siegbahn and Svartholm for a double-focusing spectrometer, which incorporates a magnetic field falling off radially with a field index designed such that horizontal and vertical focusing wavelengths become equal. Under those circumstances, focusing is obtained at a bend angle of $\sqrt{2}\ \pi$ radian from the source. Such an instrument was again constructed successfully with a bending radius of 35 cm and turned over to the nuclear spectroscopy activities of Felix Boehm and associates.

DuMond's retirement from teaching duties at Cal Tech was a gradual one starting at age sixty-five with decreasing duties, down to full retirement at age seventy. He continued research well beyond retirement—his last published papers date beyond his seventy-fifth birthday. It is noteworthy that his last research work reverted to his prime interest—the natural atomic constants. His last papers were review articles, written jointly with E. R. Cohen, of the status of the constants, and he joined his old and now retired friend and associate of his graduate student days, Harry A. Kirkpatrick, in a final, but not successful, attempt to solve the residual discrepancy in the absolute standardization of X-ray wavelengths. After that effort he stayed in contact with the researchers of his group and gave occasional lectures until ill health prevented him from continuing.

The above account gives only an outline of the highlights of DuMond's scientific work and only the briefest glimpse of his human qualities. He will be remembered for both of these for a long time. It is doubtful that the increasing specialization of physics will make it possible again for a single physicist to make as comprehensive contributions to design of apparatus, to precision measurements, and to theoretical interpretation as was done by Jesse W. M. DuMond during his lifetime.

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