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**Physics in Perspective**

# In Appreciation

# Multiple Scattering: Leslie Foldy's Winding Road Through Physics*

Philip L. Taylor and William J. Fickinger**

Leslie Foldy's diminutive stature and modest demeanor gave little clue to the powerful intellect responsible for several significant advances in theoretical physics. Two were particularly important. His 1945 theory of the multiple scattering of waves laid out the fundamentals that most modern theories have followed (and sometimes rediscovered), while his work with Siegfried Wouthuysen on the nonrelativistic limit of the Dirac equation opened the way to a wealth of valuable insights. In this article we recall some of the milestones along Foldy's path through a life in physics.

*Key words:* Leslie L. Foldy; Robert S. Shankland; Gregory Breit; Léon Brillouin; Edward Gerjuoy; J. Robert Oppenheimer; Lyman Spitzer, Jr.; Henry Primakoff; David Bohm; Siegfried Wouthuysen; Cécile Morette; Case Western Reserve University; University of Wisconsin; Columbia University; Underwater Sound Laboratory; Institute for Advanced Study; University of California at Berkeley; University of Rochester; University of Michigan; antisubmarine warfare; coherent potential approximation; Foldy-Wouthuysen transformation; Dirac equation; multiple scattering; nuclear physics; particle physics.

Leslie Lawrance Foldy (1919–2001, figure 1) was born on October 26, 1919, in Sabinov, Czechoslovakia, a country newly minted from the debris of the Austro-Hungarian Empire. His parents were of Hungarian origin, and named their son László Földi. The repercussions from an unsuccessful invasion of Czechoslovakia by Hungary earlier that year were making life difficult for the Hungarian minority, and in 1920 the family left

* Some of the anecdotes we report here were related to one of the authors (PLT) just before an event in 2000 celebrating Foldy's 80th birthday, while others were told to us over the course of the nearly forty years during which we were colleagues. Still others were uncovered during the course of WJF's research for his book, *Physics at a Research University: Case Western Reserve 1830–1990* (Cleveland: Case Western Reserve University, 2006). Other details were provided by Foldy's widow, Roma.

** Philip L. Taylor is the Perkins Professor of Physics and Professor of Macromolecular Science and Engineering at Case Western Reserve University. William J. Fickinger is Professor Emeritus of Physics at Case Western Reserve University.

**Fig. 1.** Leslie Foldy (1919–2001) at Case Western Reserve University in 1950, the year of publication of his landmark paper with Siegfried Wouthuysen (1916–1996). *Credit*: Courtesy of the Foldy family.

for the United States. There László Földi became Leslie Foldy, and in due course he enrolled as a student at Glenville High School in Cleveland, Ohio. When he realized that all of the other students had middle initials he chose for himself the letter L. Only much later was he obliged to expand this lonely letter into a complete name, and chose "Lawrance," being unaware at the time of his unconventional spelling.

Les determined during his high-school years that he wanted to be a physicist. His father reacted badly to this news, as he feared that his son would have difficulty making a living in this esoteric line of work. Les's father had an eye examination a few days later, and confided his misgivings to his ophthalmologist, Dr. Wolfenstein, who commiserated with him, saying that his own son had the same inclinations. Les and Lincoln Wolfenstein later became close friends, and both managed to make a respectable living in their chosen profession.

Les graduated with a B.S. degree in physics from the Case School of Applied Science (now Case Western Reserve University) in 1941, having written his senior thesis on crystal lattice vibrations. He then began a series of odysseys in which he traveled to study with a recommended advisor, only to find that the proposed mentor was no longer there. Robert Shankland, one of his professors at Case, had recommended that he study with Gregory Breit, and so he enrolled for a Master's degree at the University of Wisconsin in Madison. On arrival he found Breit to be on an indefinite leave of absence, but happily found a place with Léon Brillouin, whose work was familiar to him from his encounters with Brillouin zones when working on his undergraduate thesis.

Following the entry of the United States into World War II, Foldy joined Shankland in 1942 at the Underwater Sound Laboratory of the Division of War Research, which was then operated by Columbia University in New York. Strangely, his actual office was high up in the Empire State Building, which is about as far from being under water as one can imagine. There he worked on the use of sound waves to detect the presence of submarines.

The central problem here was that a myriad of tiny bubbles form behind a submarine's propeller as a result of cavitation. Sonar waves are then not just singly reflected, as they would be by the hull of a submarine, but are multiply reflected. The propeller's wake becomes an effective medium capable of refracting, reflecting, and scattering the incident sound waves. Foldy's solution to this problem was to define a scattering potential for which a single scattering would give a result equivalent to that of the multiple scattering from the actual system of randomly distributed scatterers.[1] This insight allowed calculation of the scattering profile of a large variety of systems, and has been widely adopted, not just in the field of acoustics, but also in optics, geophysics, materials science, communications, and even for conduction in quantum wires.[2]

On the 64th floor of the Empire State Building, life was not confined to equations. One Saturday, Les and Edward Gerjuoy were working together on a subtle point concerning the interpretation of sonar signals when they heard the sound of airplane engines close by. They went to the window to look out, but the building was shrouded in fog, and they could see little. Then there was an enormous crashing sound, and shards of glass dropped down past them. A military plane had flown into the 79th floor above them. Fortunately, most of the damage was limited to that floor, although an engine ended up in one of the elevator shafts. Knowing that news of this event would soon be broadcast, Les quickly sent a telegram to his wife, Roma, who was staying with relatives at the time. He told her, "I'm all right. Don't worry." Roma had not been listening to the radio, and was surprised to receive this cryptic message. Needless to say, she then worried!

During this period Foldy also did the only experimental research of his career. He went down to a lake in Florida, where the Underwater Sound Laboratory had a test station. There Les invented a device for producing the types of arrays of bubbles that might be formed behind a submarine propeller. His invention was basically like the atomizer found in a perfume spray, except that the roles of air and water were inverted, so that a jet of water would entrain a fine distribution of air bubbles.

To measure the distribution of sizes of the bubbles, Les and his friend, Yale astrophysicist Lyman Spitzer, Jr., donned diving helmets and went to the bottom of the lake.

There they measured the size of bubbles by noting the time it took for a particular bubble to reach the surface. It is amusing to imagine these two theorists, one short, the other tall, standing on a lake bottom, underwater stopwatches in hand, peering out of their bronze helmets as they tried to keep their eyes fixed on a single bubble among millions. Watching the motion of a tiny bubble as it slowly surfaced must have reminded them of measurements that Robert Millikan had made in his determination of the charge on the electron, when he had watched a slowly falling drop of oil.

Another problem posed by antisubmarine warfare was the need to have very accurate calibrations of the piezoelectric transducers used to detect the returning waves. A discrepancy of almost half a decibel appeared when signals were analyzed using the calibration charts provided by the Bell Telephone Laboratories. Les worked with Henry Primakoff to tackle this difficulty, and came up with a reciprocity theorem that allowed the transducer to be precisely calibrated by using it as a loudspeaker rather than a microphone. Their result, "that the ratio of the magnitudes of the microphone and speaker responses of a transducer is a quantity independent of its specific nature and construction,"[3] finally won the day in their long-running argument with the acoustics experts on the Bell Labs staff.

Foldy's groundbeaking theoretical work on the multiple scattering of waves could not be published until it was declassified at the end of the war,[4] and even then it hit a minor obstacle. Foldy had included a statement pointing out the wide applicability of his theory, and gave among his examples the scattering of neutrons by liquids and amorphous solids. The word "neutron" raised a red security flag at *The Physical Review*, and delayed appearance of his paper until the offending word was removed. The circumstances of its publication may have contributed to his work being overlooked by the many future authors who rediscovered this seminal theory, which now appears in the literature in many guises, such as the widely used coherent potential approximation.

After the war ended in 1945, Bob Shankland, Foldy's mentor at Case and at the Underwater Sound Laboratory, recommended that he go to the University of California at Berkeley to study for a Ph.D. degree with J. Robert Oppenheimer. Off he went, only to find that history was repeating itself: Oppenheimer was nowhere to be found or, rather, was in an "undisclosed location." Undaunted, he accepted an appointment as a Research Physicist at the Radiation Laboratory, where Luis Alvarez recognized his talents. There he worked with David Bohm, who was a former student of Oppenheimer. Bohm had been judged a security risk by General Leslie R. Groves, head of the Manhattan Project, and had even been denied access to his own thesis research on security grounds, but had been given his Ph.D. degree without examination on the basis of Oppenheimer's testimonial. Together with Bohm, Les undertook a detailed analysis of the motions of charged particles in some of the newly developed accelerators that Ernest Lawrence had constructed at Berkeley.[5]

Oppenheimer resurfaced, but was now at the Institute for Advanced Study in Princeton. Les joined him there (figure 2), while still retaining the affiliation with Berkeley that would allow him to complete his University of California Ph.D. degree. He was now able to direct his research interests to more fundamental problems. One sees this progress from the title of his somewhat heterogeneous doctoral dissertation of 1948: "Four Studies in Theoretical Physics. I. The Theory of the Synchrotron. II. The-

Institute for Advanced Study, Princeton. Eisenstaedt Life

**Fig. 2.** A seminar conducted by J. Robert Oppenheimer (1904–1967) at the Institute for Advanced Study in Princeton, in which he sits on a table strewn with ash trays and slide rules. Leslie Foldy (1919–2001) is also seated on a table on the right, Harold Lewis (b. 1923) is in front of him, and Siegfried Wouthuysen (1916–1996) is in the foreground. *Credit*: Eisenstadt – Life Magazine.

ory of the Synchro-Cyclotron. III. On the Meson Theory of Nuclear Forces. IV. The Energy-Momentum Relations for Particles Interacting with Fields."

Shankland (figure 3) was eager to persuade Foldy to join the faculty of the physics department at Case, and on completion of his thesis work Les accepted this offer, returning to his hometown and undergraduate school to become its first theoretical physicist. He was very happy to be going back to Cleveland, but expected to miss the presence of other theorists, and so accepted an invitation to spend the intervening summer with Robert Marshak and his group at the University of Rochester. He was then able to continue his scientific conversations with his Dutch friend Siegfried Wouthuysen, who also had been a student of Oppenheimer at Berkeley and Princeton, graduating in the same year as Les, and who was now spending a year at Rochester.

At that time, it was understood that Paul A. M. Dirac's 1928 equation provided a complete prescription for describing the motion of a relativistic electron, and that this theory also applied to the protons and neutrons that comprised the atomic nucleus. What was unclear was how this elegant formalism could be applied in a nonrelativistic or weakly relativistic context. In the summer of 1948, Les and Sieg worked together on the theory of how gamma rays impinging upon a nucleus can lead to the production of

**Fig. 3.** *Left to right*: Case Physics Department Head Frederick Reines (1918–1998), Case President T. Keith Glennan (1905–1995), former Physics Department Head Robert S. Shankland (1908–1982), and Leslie Foldy (1919–2001) in 1966. *Credit*: Courtesy of the Foldy family.

mesons. Some months later they produced a preprint in which they indicated what they considered to be the appropriate pathway to a nonrelativistic solution of this problem.

The following summer Les attended the Theoretical Physics Summer School at the University of Michigan, and there met Cécile Morette (later Cécile DeWitt-Morette, widely recognized for her achievements in creating the Summer School of Physics at Les Houches in the French Alps). She, too, was working on the theory of meson production. Les had missed overlapping with Morette at the Institute for Advanced Study in Princeton, where she had arrived for a two-year period of postdoctoral work with Oppenheimer just as Les was leaving. This twenty-seven-year-old Frenchwoman was a person of great charm, and usually of great tact, but this was not apparent to Foldy when she expressed the opinion that he had made an error in his preprint with Wouthuysen. There were, she claimed, some extra terms that could not be ignored. Les was sure that these terms were relativistic, and found himself intensely frustrated by his inability to convince Morette of this. Quietly seething, he went again to Rochester to spend the remainder of the summer of 1949.

Now, Foldy was the most gentle and mild-mannered individual that one could imagine. In forty years of eating lunch daily with him, we never heard him express anything more than mild irritation at any of the infuriating provocations that life throws in one's path. This disagreement with Morette, however, evidently affected him deeply, as he began a systematic effort to validate his intuition with an indisputable formalism. The key, he felt sure, was to find a way of reducing the four components of Dirac's relativistic equation to the two components of the nonrelativistic Pauli-Schrödinger equation. Fortunately, he had already studied the work of Julian Schwinger on canonical transformations, and suddenly, as he said in a later memoir, "the light flashed on in my mind." [6] He applied his idea, and saw that it worked. He could now produce an equation that clearly demonstrated the difference between relativistic and nonrelativistic terms! He showed his result to Sieg Wouthuysen, who then improved on it by showing that in certain circumstances it could be recast in a more elegant way, without the need for an infinite series of terms.[7] For the following fifty years Les and Sieg would take turns belittling their own contributions to this success, with each praising the achievement of his colleague.

The Foldy-Wouthuysen transformation (or FW transformation, as Les used to refer to it) was a milestone in theoretical physics in that it permitted many new calculations to be performed. It also shed light on the vexing question of how an electron, which is thought to be a point particle, may sometimes show some of the characteristics of a particle of extended radius.

The power of this new formalism was not immediately apparent to all in the physics community, and Foldy's star did not rise with the speed that we might have expected. His absolute refusal to blow his own trumpet with anything more than a gentle "toot" doubtless contributed to this. It was only when he showed that application of his theory to a simple scattering problem could produce radically new results that he began to achieve some of the recognition he deserved. This came about in the following way.

One of the strengths of the FW theory was that it worked, not just for free particles, but also for particles in electric and magnetic fields. This made it applicable to the problem of the interaction of an electron with the magnetic field surrounding a neutron. This idea occurred to Les one night as he was brushing his teeth before going to bed. He lay wide awake for some time, figuring out the details in his head. When he awoke the next morning he got up, sat down at a table, and wrote out his calculation for publication,[8] putting it in the mail that very afternoon! His new work eliminated a discrepancy between theory and experiment that had obstinately defied resolution for some years, and at last brought him the acclaim that was his due.

Unfortunately, this comparative fame did not earn him wide recognition of an important piece of work that he had done with his undergraduate student Fred Milford the previous year, in 1950.[9] This concerned the magnetic moments of nuclei that consist of an odd number of nucleons (protons or neutrons). The simplest theory had proposed that an even number of nucleons would form a nonmagnetic core about which the one remaining unpaired nucleon would orbit. This last particle would contribute the entire magnetic moment of the nucleus. Experimental measurements showed that this prediction was reasonably good, but that there were discrepancies. Foldy and Milford proposed in their 1950 paper that this could be accounted for by an exchange of angular momentum between the odd nucleon and the core. The mechanism for this exchange was the presence of distortions in the shape of the nuclear core, rather like the tidal distortions of the surface of the oceans by the presence of the gravitational

**Fig. 4.** Among the many well-known physicists shown in this photograph taken at the International Conference on Theoretical Physics in Seattle, Washington, in 1956 are several who are mentioned in our narrative. In the front row, Leslie Foldy (1919–2001) is third from the left and J. Robert Oppenheimer (1904-1967) is on the far right. In the second row, Julian Schwinger (1918–1994) is on the far left. In the third row, Gregory Breit (1899–1981) is on the far left and Lincoln Wolfenstein (b. 1923) is third from the left. *Credit*: Courtesy of the Foldy family.

attraction of the moon. Aage Bohr had independently conceived the same idea at the same time, and his 1951 paper,[10] submitted before but published after the publication of Les's work, formed the foundation of the research for which he, Ben Mottelson, and James Rainwater received the Nobel Prize in Physics for 1975.

Foldy had an understanding of the nature of the vacuum that was ahead of his time, and used this to show in 1954 that there could be no charged particle lighter than the electron,[11] as the presence of virtual pairs of such particles would have changed the spectrum of atomic hydrogen from its known form. In the same year he again used the concept of the polarization of the vacuum[12] to correct a discrepancy in the calculation of proton-proton scattering that Gregory Breit and his colleagues had produced.[13] This was the same Breit (figure 4) with whom Les had hoped to study at Wisconsin thirteen years earlier.

During the following forty years, Foldy's path through physics traced a serpentine route. While the core of his work stayed close to particle physics, he made frequent excursions into atomic and condensed-matter topics.[14] Those of us who had the privi-

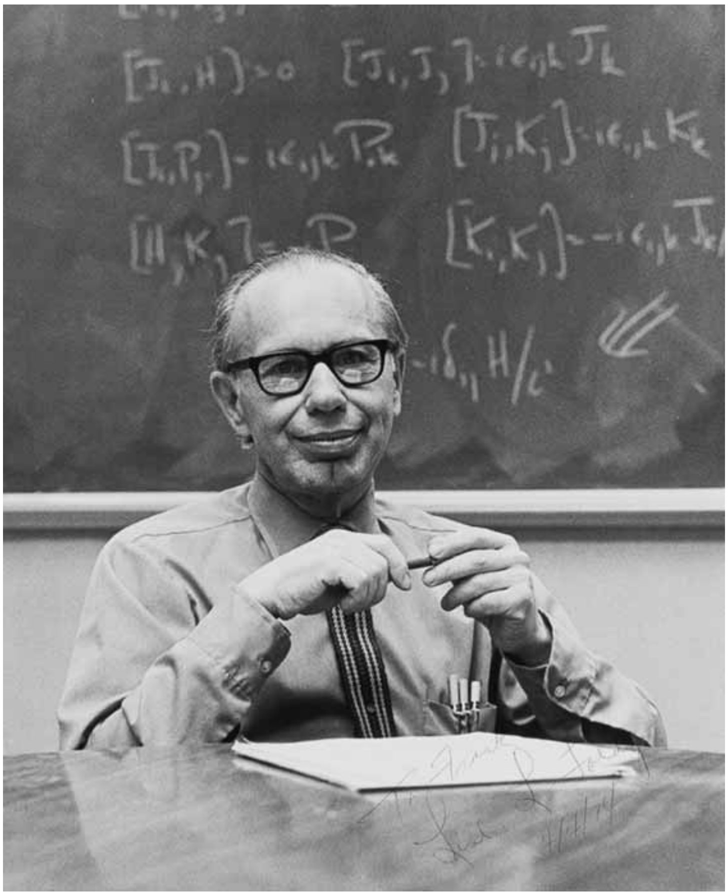

**Fig. 5.** Leslie Foldy (1919–2001) in 1974. *Credit*: Courtesy of Frank Cverna.

lege to be his colleagues at Case Western Reserve University, where he remained for the rest of his career until his death on January 18, 2001, sometimes wondered why he was never accorded the national recognition that we all felt he deserved. He was never elected to the National Academy of Sciences, for example, despite his influential role in making possible the achievements of others who were accorded this honor.

There are many probable reasons, some minor and others more significant. Les had seen the treatment that many of his friends had received during the McCarthy witch hunt in the early 1950s. Several former Oppenheimer students, including David Bohm and Foldy's future Case Western Reserve colleague Joseph Weinberg, had suffered grievously during this period, and Oppenheimer himself was, of course, not immune. Les's deep revulsion at some of the acts of the U.S. government at this time and during the Vietnam war led him to refuse to apply for federal funds to support his research. He consequently never led a group of any appreciable size.

Foldy (figure 5) received many offers of jobs on the east and west coasts, but declined them all, preferring to stay in Cleveland. His reasons probably arose from a combination of his great feeling of loyalty to his mentor Bob Shankland, and a comfort level he felt in staying in his hometown among lifelong friends. (Roma, a native New Yorker, understood her husband's feelings, even though she did not share them to such a great extent. She repressed the great vigor with which she customarily expressed her views, and was fully supportive of Les's decision not to move.) These repeated refusals to accept prestigious positions may, however, have hurt the pride of some who had issued invitations, and perhaps contributed to his being overlooked when honors were being awarded.

Les's willingness to spend his time on solving problems brought to him by others also meant that his reputation was diffused throughout numerous subspecialties of physics, and consequently not all the problems he solved were of a fundamental nature. Finally, his modest and retiring personality and his soft-spoken gentleness may have tended to create the erroneous impression that there was no powerful intellectual engine quietly thrumming away behind the deceptively unassuming façade. Nothing could have been further from the truth than such an assumption, and we who were his colleagues rejoice in having benefited from his wisdom and friendship.

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Department of Physics
Case Western Reserve University
Cleveland, OH 44106-7079 USA
e-mail: taylor@case.edu
e-mail: wjf@case.edu