Chapter 9 CIT Theorists

Foldy,	Klein,	Milford,	Winterberg,	Tobocman,	Thaler
1948-1990	1949-1967	1952-1959	1959-1963	1960-2001	1960-1981

Shankland was away from Cleveland for most of the war, working on underwater sound detection in New York City or England or Florida. When he returned to Case to resume his responsibilities as chair of physics, he appreciated the need to add research in *theoretical* physics to the department's program. His colleagues, Smith, Shrader, Crittenden, and Olsen, were all doing *experimental* physics. While experimentalists are generally familiar with the theory underlying their research, their emphasis is on apparatus and measurement. There were no "pure" physics theorists at Case. Shankland had made many contacts in his travels with young people who were developing the theories stemming from new experimental results in nuclear, particle and condensed matter physics.

Case Institute could expect to expand rapidly, especially given the increased postwar public interest in science and engineering. Many of the troops returning from the war would take advantage of the GI Bill which paid their college tuition. Quoting C.H. Cramer's history of CWRU: "By 1946 every engineering college in the land was operating beyond its normal capacity; some had set up two-shift programs to meet the emergency. At Case there was a ten-to-one ratio between applications and admissions." By 1947, there were almost 3000 students at Case, including 200 in the newly established graduate program. Shankland's student, Earle Gregg, would be awarded the department's first PhD in 1949.

Shankland enjoyed the support of two successive presidents, William E. Wickenden and T. Keith Glennan, and of the trustees, in expanding the department. Between 1948 and 1960, Case would add a half dozen theoretical physicists to its faculty. The Western Reserve department would do likewise, under chairmen Richard Beth and John Major.

With the arrival of the theorists, this history of research comes to a turning point. The earlier chapters describe experiments, including details of the techniques and apparatus employed, most often with quantitative results. Most theoretical papers, however, concern the development of new mathematical techniques or the application of old ones to organize and describe what the experimentalists have seen.

In this and later chapters, we shall give a qualitative overview of the work done by the twenty-odd theorists who become part of the physics faculty. We'll give some background on each person, and list a selection of papers including titles, and comment on a few of the highlights. Hopefully, this will allow the reader to have some appreciation for what the theorists have accomplished.

Foldy – Case's first theorist

Leslie L. Foldy was born in 1919 in Sabinov, Czechoslovakia; he was brought by his parents to America as an infant. In 1937, he graduated from Glenville High School in a European ethnic neighborhood on the east side of Cleveland. He matriculated as a student of Miller and Shankland at Case, where he would later spend most of his fifty-year career as a theoretical physicist. He would become the first theorist to join the Case department. Foldy's extraordinary productivity, his wide interests, and his friendly and cooperative nature had a major impact on the department.

Foldy graduated with a BS from Case Tech in 1941, having written his senior thesis on crystal lattice vibrations. I asked him once what his middle initial L stood for. He said that when he arrived at Case, all the other students seemed to have middle names. He had none, so he opted for a simple L. He went to the University of Wisconsin where he completed a master's degree under the famous French physicist Leon Brillouin. With the outbreak of World War II, Foldy went in 1942 to join his former professor, Shankland, at Columbia University in the Division of War Research, to work on submarine detection. Foldy quickly grasped the theoretical physics implications of the work, publishing three related papers.

In the first, Foldy looks at the scattering of waves from a random distribution of isotropic scatterers, including (and this is the main thrust of the exercise) the interference phenomena present in any wave scattering. The results are applicable to many systems, from sound waves scattered by water droplets in a fog, to electrons scattered by atoms in a crystal. Why was this of interest in submarine detection? Given a source of sound at a certain position and with a certain intensity, what would be the effective signal measured by a detector of a given geometry and size at a second position? It would have been helpful for our purposes if the equations developed in the paper were applied to some measured system, but such is not the case, as with many theory papers. "The Multiple Scattering of Waves" (*Phys. Rev.* **67** 107 1945) The ideas in this paper would be applied not only to problems in the multiple scattering of acoustical waves, but, for decades afterward, would be used in the analysis of nuclear and other scattering processes

While working in 1944 at Columbia, Foldy wrote a brief report on the possible application of Dayton Miller's mechanical integrator, the Henrici analyzer. We described this favorite device of Miller in Chapter 4. Foldy acknowledges that there are other methods to Fourier-analyze waveforms, but this one might have its advantages. He describes a shutterless movie-film camera which captures the signal from an oscilloscope face to produce transparencies which can be placed directly on the Henrici tracing bed. "The Use of the Henrici Harmonic Analyzer to Obtain Frequency Spectra of Pulses". The copy of this report in Foldy's files is stamped "…. information affecting the national defense…"

The two other Columbia papers (*Jour. Acous. Soc. Amer.* **17** 109 1945 and **19** 50 1947), written with Henry Primakoff, developed the theory of electroacoustic transducers. Here Foldy turns his attention to the physical properties of the emitters ("speakers") and detectors (“microphones”). Once again, he develops integral equations to describe the relation between the pressure and normal velocity at each point on the surface of the transducer (the input) and the voltage and current at its electrical terminals (the output). Input to the calculation are the electric, magnetic, thermal, and mechanical properties of the device. Related to this study is an examination of the validity of the “Reciprocity Theorem”, which states (quoting the first paper) “that the ratio of the microphone response of the transducer to its speaker response is a quantity which is independent of the nature and construction of the transducer.” Here he is talking about hitting the transducer with an electrical pulse and looking at the resulting mechanical response, and then hitting it with a mechanical pulse and looking at the resulting electrical response. In a 1957 letter about Foldy to the Case dean, Shankland says, “….the most interesting (contribution by Foldy) was his thorough-going proof …. that the principle of reciprocity is the most basic and useful means for the calibration of acoustical transducers. His views on this were accepted only after very vigorous opposition by the Bell Telephone Laboratories and others …. considered to be leaders in acoustical problems.”

To Berkeley

In 1945, Foldy was appointed Research Physicist at the Radiation Laboratory at University of California Berkeley. His assignment was to undertake a detailed analysis of just what is going on inside the new particle accelerators. (Ernest O. Lawrence, inventor of the circular machines, was at Berkeley.) In two papers written with young colleague D. Bohm (*Phys. Rev*. **70** 249 1946, and **72** 649 1947), Foldy presents calculations for the motions of charged particles in various types of machine.

The following spring he began graduate studies at UC Berkeley working under J. Robert Oppenheimer on the nature of nuclear forces. His doctoral dissertation had a four-fold title: “Four Studies in Theoretical Physics. I. The Theory of the Synchrotron. II. Theory of the Synchro-Cyclotron. III. On the Meson Theory of Nuclear Forces. IV. The Energy-Momentum Relations for Particles Interacting with Fields.” He spent his final year of graduate studies at Princeton because Oppenheimer had moved there from UCB.

An aside on particle accelerators. In a betatron, *electrons are injected into an evacuated space in which an applied magnetic field rises rapidly from zero to some maximum value. The changing B-field induces a tangential electric field which accelerates the electrons while the magnetic field confines them to a circular path. In a* cyclotron, *the charged particles are introduced at the center of a large cylindrical evacuated space in which there is a steady magnetic field. They are then accelerated by an alternating electric field set up between the two halves of the cylindrical space, spiraling outward until they exit the machine. In a* synchrotron, *bunches of particles are introduced into a doughnut-shaped evacuated space where they are accelerated by periodic electric fields at certain points around the ring; they are held in a fixed orbit by a magnetic field which increases in strength as the particles speed up.*

To first approximation, these various accelerators are simply described, but when one looks at details such as off-axis beam particles and their oscillations about a central orbit and the effect of energy loss by the electromagnetic radiation coming from the accelerated particles, the problem becomes a suitable challenge for the mathematical physicist. These two frequently cited papers of Bohm and Foldy present criteria for optimizing machine design so as to capture and accelerate the maximum number of particles.

Foldy and particle physics

To this point, most of Foldy's work may be described as "applied physics", and it was time for him to move on to "basic theoretical research" in nuclear/particle physics. Experiments on neutron-proton and proton-proton scattering and investigations of the deuteron (the bound neutron-proton system) had been reported and theorists were busy trying to deduce from them the nature of the short-range nuclear force. Yukawa had proposed in 1934 that the nuclear force might be due to the exchange of a spinless particle (the meson) with mass about 100 MeV (about 200 times the electron mass). Subsequently, particles with masses in this region were discovered in cosmic rays. Grad-student Foldy's task was to calculate the phase-shifts (a set of numbers which determine the np and pp scattering angular distributions and cross sections) and the deuteron properties by assuming various combinations of two-nucleon angular momentum states (as described in Chapter 6 in the section on the Shankland experiment) and the spins and masses of the exchanged meson(s). His conclusion was that better agreement with experiment could be found with the exchange of 150 MeV mesons than with 100 MeV mesons. ("On the Meson Theory of Nuclear Forces" *Phys. Rev.* **72** 125 1947) The π meson mass was eventually found to be 139 MeV. However, over the course of the following twenty years, it was became clear that several mesons with various masses and spins participate in the nuclear force.

Fig. 9-1. Bob Shankland and young Les Foldy.

Shankland was very keen on getting Foldy to join the department at Case. In 1948, Foldy accepted his offer, and returned to his hometown and undergrad school to become its first theoretical physicist. **Fig. 9-1** shows the young Foldy and chairman Shankland at the front door of Rockefeller. In a paper written with Robert Marshak (University of Rochester), assistant professor Foldy presented a calculation of the expected cross-section for the production of π mesons in nucleon-nucleon collisions. The authors point out that the new accelerators will be able to produce these particles, seen hitherto only in cosmic rays. The approach is described so: "…we have regarded meson production as a second-order process in which one step consists of the creation of a meson by one of the nucleons, and the other step consists of the scattering of the resulting nucleon by the second nucleon via the nuclear potential between them." The resulting cross-sections are given for two forms for the potential and for three energies. (*Phys.*

Rev. **75** 1493 1949) Later developments in this field, for example the role of excited states of the nucleon, superceded these calculations.

The FW transformation

A second paper was written during Foldy's year at Rochester, this time with the Netherlander Siegfried A. Wouthuysen. It is this paper for which Foldy is best known today. With the advent of quantum mechanics, in which particles are shown to behave like waves, Schrödinger proposed a wave equation which was extremely successful in describing such things as the hydrogen atom, including the prediction of all its energy levels. Later, Dirac proposed a wave equation which is applicable to *relativistic* systems. The astonishing thing about the Dirac equation was that it had solutions for both positive and negative energies and for two values of a new undefined quantum number. It was soon understood that the negative energy states describe anti-particles such as the positron, and that the new quantum number specified the two possible orientations of the spin of the particle. The bad news was that the four components of the predicted wave functions were mathematically entangled so that it was difficult to write a wave function for a given electron in a given spin state. Foldy and Wouthuysen discovered a transformation (i.e. a mathematical operation) which changed the wave function to a form which had separate solutions for positrons and electrons and separate solutions for spin-up and spin-down. The new form makes it easier to interpret the solutions of the Dirac equation, as well as simplifying the analysis of the interactions of Dirac particles with electromagnetic and other fields. Furthermore, it makes it easier to mesh the predictions of the Dirac theory with those of the non-relativistic theories in the energy region where both theories should apply. "On the Dirac Theory of Spin ½ Particles and its Non-relativistic Limit", (*Phys. Rev.* **78** 29 1950.)

Foldy soon followed up on these ideas with a short letter which pointed out that the application of the Foldy-Wouthuysen (FW) transformation to the equation describing a neutron in an external electromagnetic field predicts the value of the electron-neutron interaction (roughly parameterized as a potential well with depth 3.9 keV). He pointed out that this value is consistent with that deduced from shifts of spectral lines associated with the additional neutrons in certain isotopes. According to Foldy's colleague, Phil Taylor, Foldy "thought of this while brushing his teeth one night; worked it out and submitted to *Phys. Rev.* the next day." "The Electron-Neutron Interaction" *Phys. Rev.* **83** 688 1951.

Two back-to-back papers the following year pursued additional applications of the FW transformation. In the first, Foldy further develops the ideas of the FW paper. He explains how the interaction of Dirac particles with external electromagnetic fields, when suitably transformed, can be broken into a sum of terms representing the various moments of the charge and current distributions with the moments of the interacting field. "The Electromagnetic Properties of Dirac Particles" *Phys. Rev.* **87** 688 1952.

The second paper addresses new measurements of the electron-neutron interaction based on the scattering of thermal neutrons by atoms of monatomic gasses. (These atoms have a full shell of electrons on their outside surface which the neutron can sample.) Foldy used the techniques elaborated upon in the preceding paper to isolate the contribution of the neutron's intrinsic magnetic moment. He then ascribed the difference between the experimental value of the strength of the interaction and his calculated value (a rather wide-open 320 ± 400 eV) to a possible contribution from "meson theory". In the latter, the neutron is expected to spend part of the time as a proton and a negative pi meson, so that the electron might see the fleeting virtual charged particles. Clearly, the theory was a bit ahead of experiment, but at least an upper limit on the "meson" contribution was implied. "The Electron-Neutron Interaction" *Phys. Rev.* **87** 693 1952. A later paper returns to the neutron-electron interaction, where Foldy considers the possibility that the neutron has internal structure, with separated electric charges, which the electron will feel. (This was well before the three charged quark picture of the nucleons appeared.) "Neutron-Electron Interaction" *Rev. Mod. Phys.* **30** 471 1958. "Electric polarizability of the neutron" *Phys. Rev. Lett.* **3** 105 1959. In Chapter 8 we mentioned Marshall Crouch's experiments on the neutron-electron interaction and how they related to the Foldy calculation.

Years later, perhaps in the 1980's, Foldy wrote a five page description of the development of the FW transformation: "Origins of the FW Transformation: A Memoir". Because this paper has not been published elsewhere and the FW technique represents a significant advance in quantum mechanics, I have included, with permission from the Foldy family, the entire text in **Appendix G**.

The effective electric charges of elementary particles are modified by the presence (in the vacuum) of particle-antiparticle pairs which pop into existence for a very short time and whose electric charges change the electric fields around charged particles. This is called "vacuum polarization". Foldy pointed out that the observed effects were well explained by virtual electron-positron pairs, and that there was no need (or room) for proposed pairs of some new lighter entity. "Elementary particles and the Lamb-Retherford line shift", *Phys. Rev.* **93** 880 1954. This was followed by calculations of the effects of vacuum polarization on low energy proton-proton scattering, and on Coulomb energies in nuclei, both of which depend on the effective charges of the protons. "Some physical consequences of vacuum polarization" *Phys. Rev.* **95** 1048 1954.

Scattering theory

In the 1930's, experimental physics was largely concerned with the properties of atoms, in the 1940's and 1950's the major interest was the atomic nucleus, and in the 1960's, it was the properties of more fundamental particles, like protons, electrons, pions. This progression toward the study of smaller structures followed the development of more and more energetic beams of projectiles: 10 keV x-rays and electrons to scatter from atoms, 10 MeV gamma rays and protons to aim at nuclei, 1 GeV electrons, protons and pions to probe even more deeply. The common thread is "the scattering process", and the challenge to the theorist is to deduce the properties of the target and the nature of the interaction between projectile and target from the experimental observations. This challenge would be taken up by Foldy, by his fellow theorists Tobocman and Thaler, and later by a half-dozen other members of the Case and WRU departments.

An aside on scattering. *What happens when beam particle* ***a*** *hits a target particle* ***A****? Each of these particles can be as simple as an electron or as complex as a large atom. The simplest thing that can happen is* ***a A → a A****, i.e. the incident particle bounces off the target particle, giving it some of its kinetic energy. There is no change in the mass or internal structure of either particle. This is* ***elastic*** *scattering. Analysis of the elastic scattering of alpha particles by matter led Rutherford to discover that most of the mass of the target atom resides in a tiny positively charged ball, the nucleus.*

But many other things can happen in a scattering experiment. The particle ***a*** *might be absorbed and a new particle* ***b*** *created:* ***a A → b B****; the target* ***A*** *might become excited, reducing the energy of the incident particle:* ***a A → a A*****; new particles might be created or blasted out of the target:* ***a A → b c B****; or* ***a*** *might interact with some component of the target, chipping off a piece. All these processes take place through forces: electromagnetic, strong or weak; or, in terms of particle exchange, by the emission and absorption of the force carriers: photons, gluons, or weak bosons.*

The experimentalist measures the reaction cross sections (i.e. the probability that a given reaction will occur) and the differential cross sections (i.e. the probability that the scattered particles will travel in a given direction). It is the job of the theorist to deduce what is interacting with what, and what forces come into play.

Collisions of small particles at high energies are governed by quantum mechanics, where particles are waves, and systems of particles exist in certain allowed energy states, and collisions take place in certain allowed angular momentum states. The theorist treats the incoming and outgoing particles as waves, and the collision as characterized by a finite number of "partial waves" (i.e. angular momentum states). A quantum mechanical analysis of the scattering process yields a set of coupled partial differential equations for the partial waves. These are too difficult to solve exactly. This is where the theorist uses a bag of mathematical tricks to devise approximate solutions. Many of the papers by Foldy, Tobocman, and Thaler, and, later, of Kowalski, Kisslinger, Shakin and Brown are concerned with this sort of calculation.

One example of Foldy's important contributions to scattering theory is described in a paper he wrote with R. F. Peierls at Brookhaven in the summer of 1962. In this work, rules were derived for interactions which proceed by the exchange of a virtual particle. In particular, the theory sets limits on the values of the isotopic spin of the exchanged "entity". *Isotopic spin, then called T, is a quantum number related to the number (2T+1) of particles in a family of particles, e.g. T = ½ for the two member family of neutron and proton or T = 1 for the 3 member family of* π^+ π^0 π^-. "Isotopic spin of exchanged systems", *Phys. Rev.* **130** 1585 1963.

The Versatile Foldy

Foldy's interests were broad, concerning a wide range of physics theory. For at least four decades, the department benefited from his willingness to discuss, enlighten, and advise on almost any corner of physics research. A lot of physics was accomplished at the daily roundtable lunches in the Rockefeller building. A clear indication of the breadth of Foldy's research interests can be found in Appendix B where the titles of his students' masters and doctoral dissertations are listed. The photo of Foldy in **Fig. 9-2** was taken around 1980.

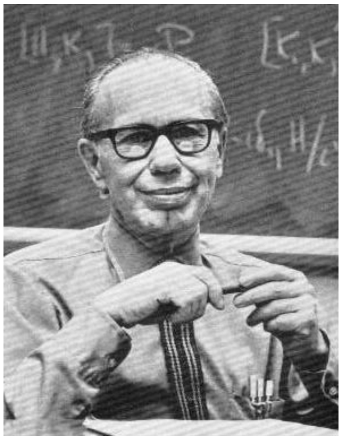

Fig. 9-2. Les Foldy.

Solids

A paper on a **classical electromagnetism** problem which Foldy wrote with colleague J. R. Reitz will be described in Chapter 17. In a paper related to the analysis of the experiments by W. L. Gordon (Chapter 11), Foldy looked at the theory of electronic energy levels in solids. "The present paper can be considered a 'derivation for experimentalists' of the (theoretical) inversion formula". "Inversion Scheme for Obtaining the Fermi surface from the de Haas-van Alphen Effect" *Phys. Rev.* **170** 670 1968. Later works present calculations of the frequency spectrum of lattice vibrations for bcc and fcc lattices and the phase transitions between them. "Phase Transitions in a Wigner Lattice" *Phys. Rev.* **B3** 3472 1971. "Electrostatic stability of Wigner and Wigner-Dyson lattices" *Phys. Rev.* **B17** 4889 1978.

Atoms

An example of Foldy's work in atomic physics is a comparison of two theoretical methods of calculating the total binding energy of the electrons in an atom as a function of atomic number. "A Note on Atomic Binding Energies" *Phys. Rev.* **83** 397 1951. Another is the work on "anticrossings" with colleague Tom Eck which will be described in Chapter 12.

Nuclei

Foldy did some work on the structure of nuclei, looking at how the magnetic properties of the nucleus could result from the individual magnetic moments of the constituent nucleons. This early paper was co-authored with undergraduate Fred Milford, whom we shall meet shortly. "On the Deviations of Nuclear Magnetic Moments from the Schmidt Limits" *Phys. Rev.* **80** 751 1950. In a paper written during a summer spent at Brookhaven, Foldy looked at the conditions for a nucleus to decay through the *simultaneous* emission of an electron and a photon. "Beta-Gamma Emission through Virtual States" *Phys. Rev.* **128** 1776 1962.

Energy loss

The processes by which particles lose energy as they pass through matter was of special interest to experimenters in their design of detectors. "Diffusion of High Energy Gamma-Rays through Matter. *Phys. Rev.* **81** 395 and 400 1951, **82** 927 1950 (with PdD student Richard K. Osborn). "Energy Degeneration of Cosmic-Ray Primaries" *Phys. Rev.* **81** 13 1951 (Fred Milford's BS thesis).

Accelerators

In 1961, Foldy, who often spent his summer months at Brookhaven Lab, did some thinking about how to improve the beams in particle accelerators. Recall that he had made significant contributions to this area back in 1947, even before he started his graduate studies. “Method for expanding the phase-stable regime in synchronous accelerators” *Nuovo Cim.* **19** 1116 1961.

Many-body problem

Foldy and his colleague Bill Tobocman (to be introduced later in this chapter) wrote a two-page paper pointing out some basic drawbacks in the application of accepted scattering theory to systems of three or more interacting particles. An example they give is scattering of a neutron from a bound state of a carbon nucleus and proton. "Application of Formal Scattering Theory to Many-Body Problems" *Phys. Rev.* **105** 1099 1957**.**

With his graduate student Richard Krajcik, and twenty years after the publication of the FW transformation paper, Foldy responded to claims by several authors that there were some problems with the application of FW theory to the electromagnetic interactions of relativistic particles. Foldy and his student point out certain omissions in the challengers’ calculations and conclude that with their inclusion, the FW form does not violate accepted theorems, since, as they playfully state, “ Theorems of such impeccable lineage demand proper respect by electromagnetic interaction Hamiltonians.” "Electromagnetic Interactions with an Arbitrary Loosely Bound System" *Phys. Rev. Lett.* **24** 545 1970.

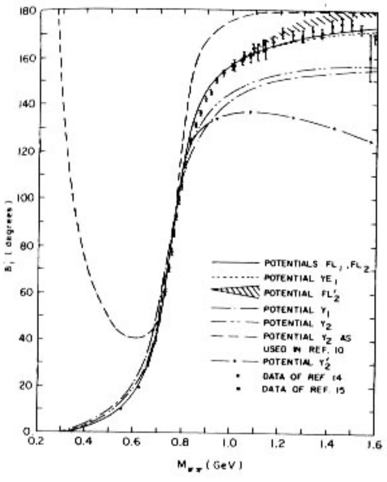

Fig. 9-3. Comparison of calculated phase shifts with experimental data.

Strong interactions

In a 1978 paper, Foldy examined data coming from the multi-GeV accelerators in which new short-lived resonant states were being discovered. He compared his calculated phase shifts with data from Brookhaven bubble chamber experiments. "A single-term separable potential with a simple analytic form which can be made to fit either experimental πN phase shifts in the Δ(1232) channel or the experimental $\pi\pi$ phase shifts in the ρ(767) channel over a much larger range in energy than has been possible with most previous single-term separable potentials is described.” (Reactions such as these will be described in Chapter 16.) **Fig. 9-3** shows the experimental $\pi\pi$ phase shifts along with a series of curves corresponding to different choices of potential. "Families of improved separable interactions for πN and $\pi\pi$ scattering for applications to three-body problems" *Phys. Rev.* **D17** 3065 1978. Foldy then sought a more fundamental description of high energy interactions. He concludes: "In summary, as an alternative to one-pion exchange S-matrix calculations, one may learn quite a bit concerning meson exchange, electromagnetic and weak currents by the application of various symmetries and conservation laws." "Symmetries, conservation principles, and the phenomenology of meson exchange currents" *Mesons in Nuclei* North-Holland Publishing Co. 1979.

In 1986, Foldy and his last graduate student, Sam Stansfield, undertook a “classical-quantum” project. The result was an interesting paper on the solution of the Schrödinger equation for a particle moving in a hypothetical potential: the superposition of a 1/r (Newton or Coulomb) potential plus a concentric harmonic oscillator potential. *Phys. Rev.* **A35** 1415 1987.

Les Foldy was appointed the first “Case Institute Professor” in 1966. He supervised the work of more than twenty doctoral students, many of whom went on to academic careers. He regularly spent summers at Brookhaven Laboratory and enjoyed productive sabbaticals at the Bohr Institute in Copenhagen and at CERN in Geneva. In a 1953 letter to Foldy, Niels Bohr writes, “you will be most welcome indeed…we have all here followed your work, which has led to so many promising results, with keen interest.” It is the opinion of many of his colleagues that Foldy could easily have found a professorship at any of the larger and more prestigious American universities. He decided, however, to remain with his friends at Case and CWRU and, with his wife, Roma, to raise his family in his hometown.

In 1993, the American Institute of Physics and the American Physical Society celebrated the 100th anniversary of the *Physical Review*. As part of that event, a committee of the AIP and APS compiled a list of the most important papers appearing in that journal. About 1000 papers were included. Les Foldy took great pleasure in going through the complete list to identify those with a departmental connection. He wrote: “Of the 979 papers, I found that at least 21 of them had an author or authors who had a connection with CWRU in that they had been students, professors, or research associates at CWRU or one of its predecessor institutions.” His list of these 21 papers appears in **Appendix E**. It includes two of his own papers: the famous FW paper and the paper on many-body scattering which he wrote with Bill Tobocman.

Foldy remained active in the CWRU physics department well beyond his retirement in 1990. In April of 2000, the department celebrated Foldy’s long career of scholarship and teaching in a day-long commemoration of his 80th birthday. The six principal speakers traced the development of the quantum theory of particles and Foldy’s contributions to it. (Gerardus ‘t Hooft, James D. Bjorken, Kenneth L. Kowalski, Frank Wilczek, Mark B. Wise, and Philip L. Taylor.) Les Foldy died in January of 2001.

Funding

Between around 1950 and 1971, the experimental and theoretical nuclear and particle physics programs at Case, and then CWRU, were supported by a blanket contract with the Atomic Energy Commission. This covered the work of Schrader *et al.* at the van de Graaff (Chapter 7) and Willard's "medium energy" group (Chapter 16), as well as all the theorists of this chapter. This arrangement ended in 1971 when Willard got DOE funding; and Thaler and Tobocman joined Ken Kowalski and Carl Shakin (Chapter 13) to establish a nuclear theory contract with the National Science Foundation. The NSF also funded Bob Brown (Chapter 13) in a separate particle theory contract. Some of the later theoretical work was funded by NASA.

Martin Klein

Chairman Robert Shankland had come to know Martin Jesse Klein when he was working on underwater sound detection during the war. On his return to Case, he would offer a position to the young theorist who was working for the government in Washington. Klein, who was five years younger than Foldy, would add a new and complementary dimension to the theory program at Case. While Foldy was, at that time, concerned mostly with nuclear and particle physics, Klein was interested in thermodynamics and the statistical mechanics of many-body systems. After finishing his doctoral work at MIT in 1948, Klein came to Case the following year. He was to play an important role in the department for almost two decades, including acting as co-chairman with WRU's Chandrasekhar at the time of the federation. His photo is shown in **Fig. 9-4**.

Fig. 9-4. Martin J. Klein

Statistical Mechanics

In the 1950's, Klein became interested in some of the condensed matter experimental work being done in the department. He published two papers on thin ferromagnetic films, written with grad students Robert Smith and Solomon Glass. They presented calculations, based on Bloch spin-wave theory, of the magnetization of such films as a function of temperature and film thickness, exactly the properties being measured by his new colleague Richard Hoffman (Chapter 12). "Thin Ferromagnetic Films" *Phys. Rev.* **81** 378 1951 and *Phys. Rev.* **109** 288 1958.

Most of Klein's work done at Case concerned basic principles of thermodynamics and statistical mechanics, often consisting of commentaries on and clarifications of earlier work by key players in these fields. The following selection of titles illustrates the wide scope of his work in the 1950's. "Classical Spin-Wave Theory" *Phys. Rev.* **80** 1111 1950. "The Ergodic Theorem in Quantum Statistical Mechanics" *Phys. Rev.* **87** 111 1952. "Principle of Minimum Entropy Production" *Phys. Rev.* **96** 250 1954. "Principle of Detailed Balance" *Phys. Rev.* **97** 1446 1955. "Generalization of the Ehrenfest Urn Model" *Phys. Rev.* **103** 17 1956. "Negative Absolute Temperatures" *Phys. Rev.* **104** 589 1956. "Grüneisen's Law and the Third Law of Thermodynamics" *Phil. Mag.* **3** 538

1958. "Thermal Expansion Coefficient of Solid He^{3}" *Phys. Rev. Lett.* **5** 363 1960. “The Laws of Thermodynamics” *Rendiconti Soc. Ital. Fis.* **10** 1 1960.

History

In the 1960's, Klein began to concentrate on the *history* of theoretical physics, an occupation he would pursue for the next four decades. He spent a year as a National Research Council Fellow in Dublin and later he was a Guggenheim Fellow at the Lorentz Institute in Leiden. While there, he wrote on Paul Ehrenfest’s contributions to quantum statistics and edited Ehrenfest’s collected papers. Returning to Case, he published a series of papers on the contributions of Planck and Einstein to quantum theory. He translated and wrote commentaries on letters about wave mechanics written by Einstein, Schrödinger, Planck and Lorentz. "Ehrenfest's Contributions to the Development of Quantum Statistics I" *Proc. Kon. Ned. Akad.* **62** 41 1959. "Max Planck and the Beginnings of the Quantum Theory" *Arch. Hist. of Exact Sci.* **1** 459 1962. "Einstein’s First Paper on Quanta "*The Natural Philosopher* **2** 1963. "Einstein and the Wave-Particle Duality" *The Natural Philosopher* **3** 1964. “Einstein, Specific Heats, and the Early Quantum Theory” *Science* **148** 173 1965. "Thermodynamics in Einstein’s Thought" *Science* **157** 509 1967.

After his short stint as acting chairman of the Case department, Klein moved to Yale University in 1967, joining the faculty as Professor of the History of Physics. He was appointed the Eugene Higgins Professor in 1974. Klein continues to write extensively on major physicists of the 19th and early 20th centuries. He has served as senior editor of four volumes of Einstein’s collected papers.

Milford – nuclear models

Frederick W. Milford completed his bachelor’s degree at Case in 1949, having published two papers with his advisor Les Foldy. These papers, mentioned above, were on very different topics: nuclear magnetic moments and energy loss by cosmic rays. The first of the two was referenced in each of the 1975 Nobel lectures by A. Bohr and B. Mottelson, not bad for an undergraduate research project.

Milford went on to MIT where he earned his doctorate in 1952; he returned to Case as an assistant professor. His work at Case continued his earlier research in nuclear theory. “The odd-nucleon-plus-liquid-drop-model of heavy odd nuclei” (*Phys. Rev.* **93** 1297 1954) and “Projection operator for the Rarita-Schwinger equation” (*Phys. Rev.* **98** 1488 1955) Milford coauthored a textbook with his colleague John Reitz: “Foundations of Electromagnetic Theory” (Benjamin Cummings 4th ed. 1993). He left the department in 1959 to take a position in industry. He eventually became the Director of the National Security Programs of Battelle, the international contract-research and technology think-tank in Columbus, where he directed 1200 staff members doing research for government and industrial sponsors.

Winterberg: nuclear dreams

In the fall of 1959, a young German nuclear theorist was invited to join the department. Thirty-year old Friedwart Winterberg had done his doctorate in natural science (Göttingen, 1955) on shell-model analyses of nuclei. He came to the United States under the "Defense Scientists Immigration Program" of the Department of Defense. This agency recruited foreign scientists "to assist in maintaining the United States in the foremost position in all phases of research and development."

Winterberg's interests were much wider, however, than nuclear theory. In Germany, he had published extensively on nuclear reactors and on nuclear propulsion of rockets, research areas clearly of interest to the US DOD. The titles of a few of his papers illustrate his potential value as a theoretical physicist, expert in strategic applications of physics: "Relativistic time dilation in an artificial satellite", "Non-linear behavior of reactors", "Nuclear fission and maximum power rockets", "Nuclear plasmas and magnetic combustion-chambers for rockets". At Case, Winterberg worked in magneto-hydrodynamics, publishing a paper in which he presented a design for a laboratory demonstration of self-sustaining hydrodynamic generators of magnetic fields. "Experimental test for the dynamo theory of earth and stellar magnetism", *Phys. Rev.* **131** 29 1963. After four years at Case, Winterberg moved on to the Desert Research Institute of the University of Nevada, where for forty years he would continue to generate ingenious ideas for the applications of nuclear fission and fusion. *Physics Today* recently reported that he was the 1991 recipient of the Oberth - von Braun Medal for his achievements in thermonuclear propulsion.

Tobocman: scattering problems

In 1960, Foldy and Klein were joined by two nuclear/particle theorists: William Tobocman and Roy Thaler. They were hired by Fred Reines who had just taken over as chairman. Nuclei and particles were indeed the hot topics in theoretical physics. Particle accelerators in the billion electron volt (GeV) range were producing beams of electrons, protons, mesons, and even light nuclei. And these beams were being used to probe all manner of targets, sometimes to learn about the internal structure of the target, sometimes to create new types of particles, sometimes to learn about the forces behind the interaction between the beam and the target particles. As was the case for Les Foldy, the mathematical techniques for analyzing scattering processes were the major interest of each of these young researchers.

Fig. 9-5. Bill Tobocman

William Tobocman came to Case in 1960. Born in Detroit in 1926, Tobocman had done his bachelors degree and his PhD (1953) at MIT. His doctoral work on the theory of deuteron stripping reactions was done under the direction of Francis Friedman. This was followed by a one-year post-doctoral position at Cornell, two years at the Institute for Advanced

Study at Princeton, a year as an NSF fellow in England at Birmingham, and three years on the faculty of Rice University. The photo of Tobocman in **Fig. 9-5** was taken around 1980.

While at Princeton, Tobocman derived a rigorous "sum-over-histories" formulation of quantum mechanics which provided an alternative approach to the formulation devised by Feynman. The sum-over-histories technique describes the passage of a system of interacting particles from a given initial state to a particular final state by summing over all possible intermediate paths. The Feynman approach was applicable to systems which can be described "classically". Tobocman's contribution successfully extended the approach to systems such as those involving spin ½ particles. "Transition Amplitudes as Sums Over Histories" *Nuovo Cim.* **3** 1213 1956.

Stripping reactions

During his postdoctoral years and the three years at Rice, Tobocman continued work on "stripping reactions". In these reactions, an incident deuteron breaks up upon collision with a nucleus. It leaves its neutron in the nucleus, while the remaining proton leaves the scene and can be detected. The angular distribution of the outgoing protons is sensitive to the angular momentum of the captured neutron, so that these measurements could provide a probe of the properties of the nucleus.

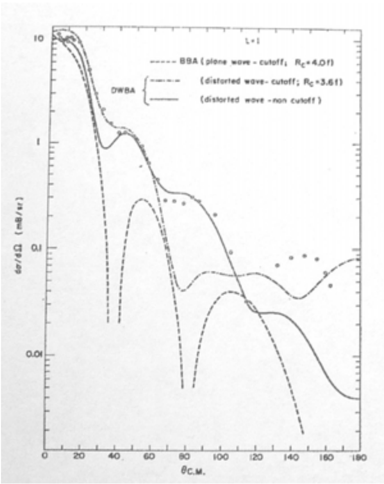

Fig. 9-6. Comparison of theory (top curve) with experiment (circles).

These calculations become more complex as one takes into account the forces between the nucleus and the incoming deuteron and outgoing proton. "Theory of the (d,p) Reaction" *Phys. Rev.* **94** 1655 1954 (at Cornell); "Numerical Evaluation of Deuteron Stripping Cross Sections and Polarizations" *Phys. Rev.* **115** 98 1959 (at Rice). Earlier calculations of this type of reaction were done "in the Born Approximation", *i.e.* the incoming and outgoing particles were described as plane waves, unaffected by Coulomb and nuclear forces. With the advent of "powerful" computers (in this case the IBM 650), Tobocman and his collaborators were able to refine the calculations, introducing suitable distortions into the single particle wave functions. "Distortion Effects in Deuteron Stripping Reactions with Low Q Values" *Phys. Rev.* **124** 1496 1961 (at Case). Tobocman was a pioneer in the use of electronic computers for nuclear physics calculations.

The results of a typical calculation are shown in **Fig. 9-6**. The theory is compared with experimental data for the deuteron stripping reaction on carbon-12. The solid curve shows how the theory can track the considerable structure in the data. "Distorted-wave Born approximation analysis of C^{12}(d,p)C^{13}" *Phys. Rev.* **136B** 1682 1964. The results of these and similar calculations were brought together in a monograph published in 1961 by Oxford University Press: "Theory of Direct Nuclear Reactions".

In the mid-1960's, Tobocman authored a series of papers on various aspects of the theory of nuclear reactions, including a half dozen with M. A. Nagarajan. This younger colleague will be introduced in Chapter 13. Tobocman spent the school year 63-64 as a Sloane Fellow at the Weizmann Institute in Israel.

Elementary particle interactions

Tobocman briefly moved up the energy scale to apply his techniques to reactions in the GeV range which were then being measured at the new particle accelerators. The observation that many collisions were "peripheral" or "glancing" indicated that "virtual" mesons hovering around a proton or other projectile were responsible for the interaction. Some of these experiments will be described in Chapter 16. A great deal of accelerator-based high energy data was well described by theories based on this idea, where the mass and even the spin of the "exchanged" particle would determine the outcome of the scattering. Tobocman examined several different interactions in the GeV range: p-p, π-p, pbar-p, etc. Two papers written with grad student David Giltinan on ρ production presented similar calculations. Here the incident π combines with the virtual π to form the ρ, and the target proton acts pretty much as a spectator to the event. "Distorted Wave Theory of the One-Meson-Exchange Reaction" *Phys. Rev.* **143** 1252 1966. "One-Meson Exchange Calculation of the $\pi^+ p \rightarrow \rho^+ p$ Reaction " *Phys. Rev.* **185** 1849 1969.

Three undergraduate physics majors were taken under Tobocman's wing, each one co-authoring with him a *Phys. Rev.* paper on nuclear reactions. So positive was the experience that all three, Myron Pauli, Richard Goldfinger, and Andrew Lewanski, remained at CWRU to complete their PhD's with him.

Many-body scattering

Tobocman moved on to calculations which treated the target nucleus as a collection of individual particles, in an approach described as "many body theory". An early paper written with Les Foldy was described above. It pointed out inadequacies in the accepted theoretical approach to this problem.. This work would serve as the starting point for a program which Tobocman would later pursue at Case for more than a decade. The calculations, as detailed in over 80 papers, would take into consideration more and more of what happens in nature: distortion of the particle waves, absorption effects, structure in the target nucleus, and the role of excited states. The culmination of this work was a comprehensive 89-page review (including 244 references), entitled "Calculable Methods for Many-body Scattering" *Rev. Mod. Phys.* **55** 155 1983.

Heavy ions

The introduction of heavy ion accelerators at several laboratories allowed the study of more complex collisions (nuclei on nuclei), and Tobocman and his colleagues and students would take an interest in their analysis. "Elastic Channel Contributions from Particle Transfer Between Heavy Ions" *Nucl. Phys.* **A202** 561 1972.

In some reactions, the incident projectile would leave two or more nucleons in the target. An example is ^{6}Li + ^{16}O → ^{4}He + ^{18}F, in which agreement with the data required that the theory should include both direct and exchange mechanisms: *i.e.* a deuteron jumps out of the lithium and into the oxygen to make the fluorine **or** an alpha jumps out of the oxygen and the oxygen absorbs the lithium to make the fluorine. "Analysis of exchange effects in the ^{16}O(^{6}Li,^{4}He)^{18}F and ^{16}O(^{3}He,^{1}H)^{18}F reactions" *Phys. Rev.* **C15** 686 1977.

A different kind of nuclear reaction is spontaneous radioactive *decay*, where sufficient energy is already sitting in the nucleus. The process will occur if and when the components of the nucleus jiggle themselves into a configuration where some sort of energy barrier is overcome – like shaking a bowl full of marbles until one collects enough energy to fly over the edge. "Calculation of the Lifetime of a Metastable System" *Phys. Rev.* **174** 1115 1968. "Comparison of methods for calculating decay lifetimes" *Phys. Rev.* **C17** 2205 1978. "Alternative treatment of exchange effects in the theory of radioactive decay" *Phys. Rev.* **C18** 1857 1978.

Scattering of ultrasound

By the 1980's, interest in scattering from nuclei had largely been replaced by high energy studies with multi-GeV probes incident upon simple targets, where the collisions are best described by quantum chromodynamics and more fundamental components: leptons, quarks and gluons. Many of the calculational techniques were similar to those used for lower energy nuclear work. Tobocman decided, however, rather than moving into "particle physics", he would apply his skills to a very different research area: the scattering of ultrasound waves.

Starting around 1985, he worked in the exciting field of "medical imaging". With the development of intense and well-controlled sources of ultrasound and of fast computers, the medical applications of ultrasonic imaging were proliferating. Tobocman found a home in this new field, successfully applying inverse scattering techniques. A *direct* scattering analysis determines the properties of the scattered waves from knowledge of the incident beam and the target profile. An *inverse* scattering analysis determines the properties of the target profile from knowledge of the scattered waves and the incident beam. His work on the application of inverse scattering theory to medical imaging with ultrasound has been published in two dozen articles in the *Journal of the Acoustical Society of America*, *Ultrasonics*, and similar dedicated journals. Methods of reconstruction developed by Tobocman and his students have been "found to yield high resolution images of small tissue structures that are free of speckle". Their method, in fact, has been awarded a U.S. patent.

Tobocman's experience in being able to move from traditional "pure" physics research into a very different area involving applications to technology has been shared by an ever growing number of theorists and experimentalists. Several other members of the CWRU physics department have succeeded in similar transitions, for example to magnetic resonance imaging and to biomagnetic diagnostic technology. We shall describe some of this work in later chapters.

Bill Tobocman retired from the department in 2002 after more than 40 years of teaching, service and research at CWRU. He was advisor to eleven doctoral students and a long series of post-doctoral associates.

Raphael (Roy) Thaler

Roy Thaler was born in Brooklyn in 1925, earned an AB at New York University in 1947 and his doctorate at Brown University in 1950. His dissertation was on a problem in atomic physics: calculation of the electron affinity of the sodium atom. He held a post-doctoral position at Yale in 1952-54 with Gregory Breit, studying relativistic corrections to magnetic moments of nuclei. He then produced a series of papers on nucleon-nucleon scattering in the 200 MeV range. He moved to a position at the Los Alamos Scientific Laboratory from 1955 to 1957 where he studied Coulomb excitation of nuclei. *(This involves calculating the probability that a target nucleus would be raised to a particular excited state when a charged particle passes nearby.)* A photo of Thaler, taken around 1980, is shown in **Fig. 9-7**.

Fig. 9-7. Roy Thaler.

During the following two years, Thaler alternated between MIT and LASL, continuing his study of “intermediate energy” scattering processes, before joining the Case department in 1960. During his tenure at Case, Thaler would spend many summers at the Los Alamos Laboratory, maintaining a connection with the research program there throughout his career. His habitual western-style string-tie declares his fondness for the lifestyles of New Mexico. Thaler would spend twenty years in residence at CWRU. He co-authored about fifty papers during that period. He worked with his colleague Carl Shakin during the three years Shakin was at Case, then with post-doc Alan Picklesimer and later with Peter Tandy who was at Kent State. Most of these collaborative works included comparisons of the theoretical calculations with experimental data coming from a variety of accelerator-based experiments.

Analysis of accelerator data

An early paper, published with Tobocman’s graduate student Giltinen, was on the proton-proton interaction. They compared their model, one based on a potential with a hard-core surrounded by monotonic attraction, with experimental phase shifts at 310 MeV. The data came from pp-scattering experiments at the cyclotron of the Radiation Laboratory at UC Berkeley. "Nonlocal Nucleon-nucleon Interaction" *Phys. Rev.* **131** 805 1963.

Working with Case colleague John Rix, Thaler proposed techniques for unraveling the strong and electromagnetic contributions to the scattering process. From the abstract: “Specific prescriptions, involving only the use of observed scattering data, are derived for obtaining the connection between the idealized “strong” scattering amplitude and the observed full scattering amplitude." "Separation of Strong and Electromagnetic Effects in Charged-Particle Scattering" *Phys. Rev.* **152** 1357 1966. At about this time, Thaler co-authored a book with Leonard S. Rodberg. "Introduction to the Quantum Theory of Scattering", Academic Press, New York 1967.

The backward scattering of neutrons with energies up to 750 MeV from protons was the subject of a subsequent paper. The data came from experiments at the Penn-Princeton accelerator. Collisions in which the neutron emerges from the collision traveling (in the center of momentum frame) in a direction opposite that of the incident neutron are interpreted as "charge-exchange", in which the neutron and proton switch identities by exchanging a charged pion as they fly by one another. The "One-pion Contribution to Neutron-proton Charge-exchange Scattering" *Phys. Rev. Lett.* **25** 1065 1970.

In a paper written with colleagues Kowalski and Shakin, Thaler discussed the effects on the scattering process of the existence of bound states in the projectile-target system. Even though the total energy of the collision may be quite different from the energy of the bound state, the latter's existence will affect the interaction. This paper offered ways to take such effects into account. "Off-Shell Contributions of the Two-Particle Transition Matrix with Bound States" *Phys. Rev.* **C3** 1146 1971.

Scattering from nuclei

Thaler worked with a series of collaborators, including colleagues from within the Case department and post-doctoral assistants. Between 1971 and 1974, Thaler would publish 14 papers in APS journals with Carl Shakin (Chapter 13). These concerned various details of scattering processes, e.g. off-shell effects and center-of-mass motion in many-particle systems. For the next four years, Thaler and post-doc D. Ernst continued the program, looking at scattering of nucleons from nuclei and developing techniques for tracking the incident particle through the target nucleus, as it interacts with one nucleon after another. A paper with post-doc E. R. Siciliano proposes an interesting technique for describing this multi-step process as an expansion of terms, the first for collisions with a single nucleon, the second involving pairs of target nucleons, and so on. "Spectator expansion in multiple scattering theory" *Phys. Rev.* **C16** 1322 1977.

Further developments in this work involved the inclusion of distortions of the scattered waves, similar to the calculations by Tobocman as described above. Thaler and Siciliano were joined by Kowalski in looking at what happens to π mesons as they plough through nuclear material. "Composite-particle structure of pion-nucleus amplitudes" *Phys. Rev.* **C19** 1843 1979. *Phys. Rev.* **C22** 2321 1980. For the next four years, Thaler worked mainly with Siciliano, Pickelsimer, and Tandy. Quoting Peter Tandy: "In about mid-late 1981, Alan (Pickelsimer) joined with Roy and me in a major research project on elastic and inelastic N-nucleus scattering in response to some interesting high-precision data starting to come out of LAMPF at Los Alamos." These data included measurement of the analyzing power (left-right asymmetry) in the elastic scattering of polarized protons by a variety of nuclei. The very high statistics of the data allowed one to take the theory to a more detailed level. **Fig. 9-8** shows a sample of the data along with two sets of calculated theoretical predictions, the dashed curves representing a theory without “relativistic” corrections, the solid curve one with these corrections. The relativistic (or “Dirac Signature”) corrections included the treatment of the incident proton as an emitter and re-absorber of virtual nucleon-antinucleon pairs in the field of the target nucleus. Even though the predicted effects are tiny, it can be argued that the Dirac model wins out (especially in the analyzing power data). “Characteristic Dirac Signature in Elastic Proton Scattering at Intermediate Energies” *Phys. Rev. Lett.* **52** 978 1984.

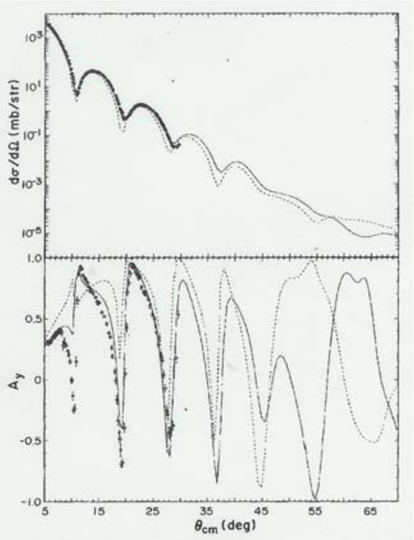

Fig. 9-8. Polarized proton scattering data compared with theory.

The Los Alamos accelerator continued to pump out high statistics data on scattering from nuclei, much of which attracted the attention of Thaler and his partners. Pickelsimer, Siciliano, Tandy, Case PhD Gary Chulick and Thaler all became members of the LAMPF scientific staff, some remaining for many years.

In the mid-80’s, Roy Thaler took an extended leave of absence from CWRU, eventually resigning his position on its faculty. He continued to publish work on nucleon-nucleus scattering theory until the mid-1990’s, while at LAMPF or Vanderbilt.