Chapter 13 Nuclear and Particle Theory

Kowalski,	Nagarajan,	Pearle,	Rix,	Kantor,	Shakin,	Brown
1963-	1964-69	1966-69	1967-70	1967-74	1970 -73	1970-

With Foldy, Tobocman and Thaler on board, the Case department had a solid base in nuclear and particle theory. Between 1963 and 1970, *seven* more hires were made in this area. Of these, only two, Kowalski and Brown, would remain in the department longer than five years. Initially, Kowalski would work in nuclear scattering theory and Brown in higher energy particle theory. Like their colleague, Bill Tobocman, both would eventually apply their mathematical talents to other areas of physics.

Kenneth L. Kowalski

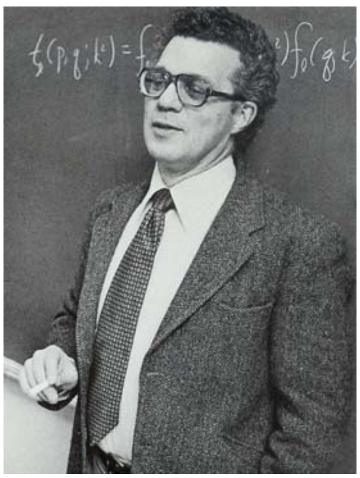

Fig. 13-1. Ken Kowalski.

Ken Kowalski was born in Chicago in 1932. He earned his bachelors degree at the Illinois Institute of Technology in 1954, and then spent three years at NACA-Lewis (The precursor to NASA-Glenn) in Cleveland where he studied supersonic flow and fluid mechanics. He subsequently enrolled at Brown University. He completed his doctorate there in 1963, working with David Feldman. His dissertation title: "On the Two-Body Formulation of High-Energy Nuclear Scattering Problems". Kowalski's work at Brown was related to theoretical studies being done at Case by Foldy, Tobocman, and Thaler, and by Kisslinger at WRU. The opportunity to work with these senior nuclear theorists played a significant role in his decision to join the Case faculty in 1963. A photo of Kowalski is shown in **Fig. 13-1.**

Between 1963 and 1983, Kowalski would tackle a series of topics in collision theory, in both the nuclear physics and the high-energy, or hadronic, domains. There would be continual overlapping of these pursuits, so we shall present them roughly by subject, saying a few words and citing a paper or two for each.

"Very" high energy hadronic scattering

This early work addressed certain features of the high-energy, low momentum transfer (i.e. glancing) collisions which were beginning to be studied at the new proton accelerators. In one paper, predictions, derived from very basic mathematical assumptions (analyticity and unitarity), are made for the shape of the angular distribution in the forward direction at very high energies. "Lower bounds on the Shrinking of Diffraction Peaks", *Phys. Rev.* **137B** 1350 1964.

Scattering from the deuteron

What happens when a proton of 10, 20 or 100 MeV scatters elastically from a target deuteron? It sees a proton-neutron combination with a net spin of one unit, rather loosely bound together, with which it interacts through both the Coulomb force and the nuclear force. The collision may involve various (and interfering) values of total angular momentum. Clues for what is happening come from the experimental angular distributions and polarizations of the outgoing protons. A large amount of such data became available in the early 1960's. Starting with the 1963 paper written with Feldman, Kowalski would pursue this problem for over two decades, introducing different calculational techniques and different assumptions. This would mark the start of his interest in "more-than-two-body interactions".

The abstract of the 1963 paper describes the early stages: "Some formal and practical problems concerning the effects of the internal target nucleon motion and of the multiple scattering on the elastic scattering of high-energy nucleons by deuterons are considered. In order to provide a foundation for the examination of these effects, two well-known forms of the impulse approximation are studied within the context of a multiple-scattering formalism…. The direct use of the optical-model approach is shown to be impractical for very light nuclei and, in particular, for the deuteron. An alternative means of obtaining solutions of the multiple-scattering equations (when the number of target nucleons is small) which permits the exact treatment of the ground-state scattering while allowing a systematic treatment of the contributions due to the excited intermediate nuclear states is discussed" "Elastic Nucleon-Deuteron Scattering" *Phys. Rev.* **130**, 276 1963. In one of the subsequent papers, Kowalski demonstrated the sensitivity of the polarization of the outgoing neutron to the D-wave part (i.e. the part with 2 units of angular momentum) of the deuteron wave function. "Two-nucleon interactions, the unitary model, and polarization in elastic nucleon-deuteron scattering" *Phys. Rev.* **C5** 306 1972.

Some terms: The ***optical model*** *picture is one in which the scattered particle is described by quantum mechanical waves spreading outward in a pattern similar to that formed by a plane optical wave incident on an opaque disk. At a more technical level, the model provides a way to calculate the "optical potential" from the basic nucleon-nucleon interaction and the wave function of the target nucleus. The* ***impulse approximation*** *describes the interaction as one in which the beam particle scatters from only one of the nucleons in the deuteron, its partner barely aware of the altercation. In the case of* ***elastic scattering****, the final state deuteron is somehow reconstituted and survives the collision. The* ***polarization*** *of the protons leaving the p-d collision is measured by using an incident beam of polarized protons, and observing the number scattered left and right.*

Off-mass-shell processes

Off-shell scattering refers to the fact that in scattering from a complex target, such as a nucleus, the participating particles can be "virtual" or "off their mass-shell", that is their effective mass-squared differs (briefly) from their energy-squared minus their momentum-squared: $m^2 \neq E^2 - p^2$. In what Kowalski describes as his most widely cited paper, he introduced new techniques for the solution of integral equations which arise in calculating the amplitudes for off-shell scattering. This paper addressed the questions of how to handle the short-range repulsion in the nuclear force and how to separate the off-shell and on-shell contributions. "Off-shell equations for two-particle scattering" *Phys. Rev. Lett.* **15** 798 1965. Because the nuclear force has only a short range, one may ignore "distant" collisions, i.e. collisions with large orbital angular momentum. In a following paper, Kowalski compares the contributions from these states for on-shell and off-shell scattering. "Angular Momentum Dependence of Off-Shell Amplitudes *Phys. Rev*. **163**, 1030-1031 1967

Three-(and more)-particle scattering

The study of the proton-deuteron, three-pion and similar "three-particle" systems resulted in a series of papers. The idea was to improve on earlier approaches in which the effects of three two-particle forces are combined. For over a decade, Kowalski, along with several of his colleagues and post-docs, would investigate techniques for calculating the details of such interactions. The integral equations which arise are enormously more complicated than those which describe two-body collisions. It was found, however, that the quantum mechanics rules for the identical interacting nucleons helped to make the calculations somewhat more manageable.

In the 1960's and 70's dozens of strongly interacting, mostly short-lived, particles were discovered at the high energy accelerators (see for example Chapter 16). Some of these decay into three particles, such as the omega meson which decays into three pions. Kowalski and collaborators applied some of the techniques developed for the 3-nucleon system to the 3-pion system. One study addressed the possibility that the newly discovered mesons which decay into three pions might be described by combinations of two-pion scattering amplitudes. "Minimal 3-to-3 Scattering Amplitudes" *Phys. Rev*. **D7** 2957 1973. "Three-pion Scattering Amplitudes and the K-matrix Formalism" *Phys. Rev*. **D13** 2352 1976. Eventually, all the mesons would be better described as quark-antiquark combinations.

Optical potential scattering

In the early 1980's Kowalski and post-docs Alan Picklesimer (Roy Thaler's collaborator mentioned in Chapter 9) and Rudy Goldflam wrote a series of papers expanding on the use of the optical model. These addressed the application of an optical potential approach to multi-body processes. From an abstract: "dynamical equations for the optical potential are obtained starting from a wide class of N-particle interactions....with arbitrary multiparticle interactions....including all effects of nucleon identity." "Dynamical equations for the optical potential" *Phys. Rev*. **C 23** 597 1981.

Relativistic pion nucleus scattering

As described in Chapter 9, Kowalski joined Roy Thaler and post-doc E. Siciliano to study the scattering of pions by nuclei. This followed the development of pion beams at Los Alamos and their use as probes of nuclei. The multiparticle aspect of these interactions was clearly within Kowalski's area of expertise. This time, however, the pions were relativistic, and the calculations required relativistic quantum field theory. "Connected-kernal multifermion Bethe-Salpeter equations" *Phys. Rev*. **D20** 2526 1979. "Composite-particle structure of pion-nucleus amplitudes" *Phys. Rev*. **C19** 1843 1979.

In 1982, Kowalski joined in some work which his colleague Bob Brown had been doing on the origins of zeros predicted to appear in the angular distributions of gauge boson scattering. "Classical radiation zeros in gauge theory amplitudes" *Phys. Rev*. **D28** 624 1983. We shall take a look at this in the section on Brown later in this chapter.

Thermal field theories

It was a distinctly different branch of many-particle physics which interested Kowalski in the mid-1980's, in particular during his sabbatical at Argonne National Laboratory. Thermal field theories, or "finite temperature field theories", are a combination of statistical mechanics and quantum field theories. They have applications to particle physics, cosmology, and condensed matter physics. Among his papers on this topic is "Real-time Fermion thermal field theories", *Phys. Rev*. **D35** 2415 1987.

In 1988 Ken organized the first truly international conference hosted by the CWRU physics department: *The Workshop on Thermal Field Theories and their Applications.* The 558-page proceedings were published in their entirety in a major European journal: *Physica* **A158** 1 1989. In light of the wide interest in this developing field, a report on this workshop was included in the popular voice of particle physics, the *CERN Courier* **29** 21 1989. This event was the first in an ongoing series of international conferences on this topic.

Non-linear Optics

Kowalski entered into a very different partnership within the department, this time with experimentalist Ken Singer. Singer (Chapter 18), who arrived in 1990, studies non-linear optical materials and has advised a significant cadre of graduate students. It was much appreciated, therefore, when Kowalski, who had many times taught the graduate course in electromagnetic theory, became interested in the theory of non-linear optics and developed a course for the graduate students. Furthermore, Kowalski, Singer and grad student Jim Andrews published a theory paper on non-linear optics. "Pair correlations, cascading, and local-field effects in nonlinear optical susceptibilities" *Phys. Rev*. **A46**, 4172 1992.

Experimental Physics at the Tevatron

In 1988, a young particle theorist joined the department. Cyrus Taylor's interest in some theoretical aspects of very high energy scattering led him, in 1993, to participate in a proposal for an experiment at the Tevatron proton accelerator at Fermilab. We shall describe Taylor's work in Chapter 18. Ken Kowalski joined Taylor and his collaborators on the proposal, and participated in the subsequent experiment. The experiment, named

MiniMax, was run at the Tevatron in 1995 and 1996. Kowalski would, in fact, spend the fall semester of 1993 at Fermilab. The principal purpose of MiniMax was a search for "disordered chiral condensate". Basically, this effect is related to the relative rates for the production of charged and neutral pions in very high energy collisions. The experiment required the detection and identification of charged and neutral particles produced at low momentum transfers (i.e. at very small angles) in proton-antiproton collisions at 1.8 TeV center of mass energy. We shall write a bit more about MiniMax in Chapter 18. "Search for disoriented chiral condensate at the Fermilab Tevatron" *Phys. Rev.* **D61** 32003 2000.

More recently, Kowalski has become interested in theoretical particle astrophysics, specifically the origins and properties of cosmological magnetic fields. Research in theoretical cosmology by several members of the current department will be the subject of Chapter 18.

The **funding** for research in theoretical nuclear and particle physics came from grants by the Atomic Energy Commission and later the National Science Foundation. Typically, these funds provided for faculty summer salary (2/9 of academic year salary), salary for post-docs, stipends for graduate students, travel expenses for meetings and conferences, computer costs, sometimes a bit toward secretarial services, and up to 40 or 50% overhead to the university. This would add up to about $50K to $75K per year per faculty theorist.

Kowalski was chairman of the CWRU department from 1971 until 1976. He took advantage of two year-long sabbaticals, the first in 1968 as visiting professor at Leuven (Louvain) in Belgium and the second in 1986 at Argonne National Laboratory. In 1987, Ken was co-chairman, with Bill Fickinger, of the "Modern Physics in America Symposium", part of the celebration of the centennial of the Michelson Morley experiment. The proceedings of that event, co-edited by Kowalski and Fickinger, were published as AIP Conference Proceedings No. **169**, 1988. (A list of speakers and titles appears in Appendix D.) In 1991, Ken published a book on scattering theory which brought together much of his earlier work. The book was co-authored by S. K. Adhikari, who was, at the time, on the faculty of the Federal University of Pernambuco in Brazil. "Dynamical Collision Theory and Its Applications" Academic Press 1991 494 pp.

Five more theorists

Nagarajan: nuclear models

Mangalam A. Nagarajan came to the Case department as a research assistant in 1962 and two years later was appointed to the faculty. He was born in India in 1933 and awarded his doctorate at the University of Calcutta in 1962. His principal interest was the theo`ry of nuclear structure and reaction mechanisms. Among his publications while at Case were three co-authored with Bill Tobocman (Chapter 9). "Equivalence of Elementary and Composite Particles" *Phys. Rev.* **137** 1236 1965. "Boundary Condition Constraints for the Shell Model: A Method for Nuclear Structure and Nuclear Reactions"

Phys. Rev. **138** B1351 1965. "Test of the Boundary Condition Constraint Method for Nuclear Reactions" *Phys. Rev.* **140** B63 1965.

The *shell model* gives the best description of the energy levels in nuclei. *This model for loading protons and neutrons into nuclei is similar to the Bohr picture of an atom, in which electrons are forced to fill successive shells in order to have unique quantum numbers (thus satisfying the Pauli principle). The shell model predicts energy levels and quantum numbers for the nucleons in both the ground and excited states of the nuclei.* Nagarajan joined the many nuclear theorists who were developing and applying the shell model. "Separability of Center-of-Mass Motion in the Nuclear Shell Model" *Phys. Rev.* **135** B34 1964. "A Shell Model Calculation for the Reaction $N^{15}(p,n)O^{15}$" *Nucl. Phys.* **A113** 412 1968.

Fig. 13-2. M. A. Nagarajan.

Nagarajan also worked on stripping reactions in which an incoming deuteron projectile leaves its proton behind in a target nucleus. We described this process in the section on Tobocman in Chapter 9. "The Study of $B^{10}(d,n)C^{11}$ and $B^{11}(d,n)C^{12}$ Reactions" *Nucl. Phys.* **A93** 190 1966. Nagarajan remained at Case for a total of seven years. Interest in nuclear theory was waning as subnuclear theory was waxing. Nevertheless, Nagarajan would contribute to the understanding of medium energy (d,n), (t,p) and similar stripping processes in nuclei for at least two more decades. He has been part of theory-experiment collaborations at Lawrence Berkeley Lab, Saclay, and Oak Ridge. His principal base has been the Daresbury Lab in England.

Pearle: relativity, philosophy

Fig. 13-3.
Phillip Pearle.

Another young theorist hired by Case just before the 1967 creation of CWRU was **Phillip Pearle**. **Fig. 13-3.** Born in New York City in 1936, Pearle did both his BS and PhD (1963) at MIT. He then took a position as instructor at Harvard where he wrote a paper whose title suggests an independent approach to physics: "Alternative to the Orthodox Interpretation of Quantum Theory" *Amer. J. Phys.* **35** 742 1967.

Pearle's principal interests were relativistic classical mechanics and the philosophical aspects of quantum mechanics. As an assistant professor (and an extremely popular teacher), Pearle published several papers in these areas, including "Construction of an Invariance from a Conservation Law, and Vice Versa, in Classical Mechanics" *J. Math. Phys.* **9** 1092 1968. "Relativistic Classical Mechanics with Time as a Dynamical Variable" *Phys. Rev.* **168** 1429 1968. Pearle remained at the newly merged CWRU for only four years, joining the others who were squeezed out of the oversized department. Pearle has been at Hamilton College for the past 35 years, where he has continued to publish regularly on similar topics.

Rix: hadronic collisions

In 1965, the Case department added a fresh PhD to its growing group of particle theorists. **John Rix** started as a post-doc and was promoted to assistant professor in 1967. **Fig. 13-4**. Rix was born in 1938 in the Cleveland suburb of Bay Village, did his BS at Cal Tech (1960) and his PhD at Harvard (1965). Working under Walter Gilbert, he wrote his thesis on dispersion relations. In his letter of application, he described his research as "dispersion relations for charged particle scattering with particular emphasis on Coulombic competition with short range forces." This work was published after his arrival at Case in a paper coauthored by M. B. Halpern of UC Berkeley: "Exact Solution of the One-Photon-Exchange N / D Equations" *Phys. Rev*. **147**, 984 1966.

Fig. 13-4. John Rix..

Rix then worked with Roy Thaler (Chapter 9) on essentially the same topic: interference between the Coulomb and strong interactions. The authors developed a technique which uses the experimentally determined Coulomb scattering amplitudes in conjunction with the data from the scattering of charged particles by nuclei to deduce the "pure" nuclear (i.e. strong) scattering amplitudes. They include in their prescription modifications for relativity and for spin. "Separation of Strong and Electromagnetic Effects in Charged-Particle Scattering" *Phys. Rev*. **152**, 1357 1966.

The mass of the neutron is about a tenth of a percent, i.e. 1.29 MeV, greater than that of the proton. After the discovery of the π meson which clearly played a role in the nuclear force, it was not unreasonable to look at a model in which the neutron is a bound state of a negative pion and a proton. Rix took a look at a variation of this idea in which the neutron is not a simple atom-like bound state, but a dynamic system in which virtual pions are emitted into a "pion-cloud" and reabsorbed. "Remarks on the Nucleon Mass Difference" *Phys. Rev.* **158**, 1600 1967. Not very long after Rix's efforts, the quark-gluon picture of the nucleons would emerge as a better model for hadrons.

Rix supervised the work of one doctoral student, Gee-Yin Chow. In the 1960's, a large amount of data on "high" energy scattering was being generated at the accelerators of CERN, Brookhaven and Berkeley. The elastic collisions of nucleons and mesons were found to be dominated by small angle diffractive scattering and the size, shape, and width of the small angle differential cross sections were becoming available. Rix and Chow developed a consistent theoretical description of these data, including calculations for the charged particle multiplicities. "Elastic Diffraction Scattering of Hadrons at High Energies" *Phys. Rev*. **184** 1714 1969. "Distribution over the Number of Prongs in Inelastic

Hadronic Collisions" *Phys. Rev.* **D2** 139 1970. John Rix left the newly formed (and oversized) combined department in 1970.

Kantor: high energy scattering

Fig. 13-5. Paul Kantor.

Paul B. Kantor earned his PhD under Sam Treiman at Princeton in 1963. He then spent two years each at Brookhaven and SUNY Stonybrook before joining the CWRU department, at age 29, in 1967. He had been recommended to Chandrasekhar by Leonard Kisslinger (as had another Brookhaven physicist, Keith Robinson). Kantor's earlier work concerned nucleon-nucleon scattering in the intermediate (a few hundred MeV) energy range. Of special interest was the spin-dependence and predictions of polarization in high energy scattering.

At CWRU, Kantor investigated polarization in the scattering of K mesons by nucleons. Experimental data were becoming available as kaon beams were created at the particle accelerators. "Polarization in K-Nucleon Scattering" *Nuovo Cim.* **84** 353 1969. Another topic having its origins in accelerator experiments was the production of intermediate short-lived resonant particles. Kantor looked into various potential sources of symmetry-breaking such as that observed in the decay into three pions of the η meson: $\eta \rightarrow \pi^+ \pi^- \pi^o$. He and grad student Keith Taggert looked into the role of interference with competing intermediate channels (e.g. $\pi^- p \rightarrow \eta\ n \rightarrow 3\pi\ n$ which gives the same final state as $\pi^- p \rightarrow \Delta^- 2\pi \rightarrow 3\pi\ n$).

Kantor was promoted to associate professor in 1969. In 1972, he became interested in communication theory and information systems. He decided to join the faculty of the newly formed Complex Systems Institute in the CWRU School of Library Science, while retaining an adjunct position in the physics department. In 1976, Paul left CWRU to create an information retrieval "think tank", Tantalus Inc., which he heads to this day. He has been at Rutgers University since 1991 where, as Distinguished Professor, he is active in information retrieval technology and related areas.

Shakin: interactions with nuclei

Fig. 13-6. Carl Shakin.

The fifth addition to the nuclear theory group was **Carl M. Shakin** who arrived in 1970. **Fig. 13-6.** Born in 1934, Shakin did his BS in 1955 at NYU, followed by a Fulbright at Manchester and his PhD at Harvard in 1961. After a post-doc position at ITP in Copenhagen, Carl was a member of the faculty at MIT for five years before being appointed associate professor at CWRU.

In the course of the following four years, Shakin worked largely with Roy Thaler on a wide range of nuclear scattering problems. An early paper, coauthored with both Thaler and Kowalski, explores techniques for calculating nuclear transitions induced in energetic collisions. "Off shell continuations of the two particle transition matrix with bound states" *Phys Rev*. **C3** 1146 1971. This was followed, during the next three years, by no fewer than thirty-two publications with his new colleagues. Among these were the following examples, in which the general theme is the investigation of nuclear structure by scattering experiments using beams of photons, pions, kaons, or nucleons. "Theory of Analog Resonances" *Rev. Mod. Phys.* **44** 48 1972. "Nuclear γ Rays Following K^- Capture" *Phys. Rev.* **C5** 238 1972. "Intermediate Structure and the Photodisintegration of O^{16}" *Phys. Rev*. **C5** 1898 1972. "Charge-Dependent Effects in the Photodisintegration of ^{4}He." *Phys. Rev. Lett.* **28** 1729 1972. "Elastic Scattering of Nucleons from Correlated Nuclei" *Phys. Rev*. **C7** 494 1973. "Off-shell Effects in Nucleon-nucleus Scattering" *Phys. Rev.* **C7** 2346 1973. "Off-shell Effects in Elastic Pion-nucleus Scattering" *Phys. Rev*. **C9** 1370 1974. "Unitarity and off-shell Effect in the Impulse Approximation" *Phys. Rev.* **C9** 1374 1974.

Shakin took a leave of absence in the 73-74 academic year, continuing his research at Brooklyn College of the City University of New York. Even though he had just been promoted to full professor at Case, he decided to remain at CUNY. For the past thirty years, Shakin has continued to contribute prolifically to particle theory. His departure was a major loss for the CWRU theory program.

Robert W. Brown

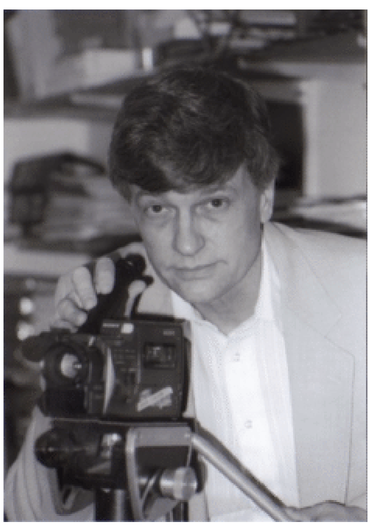

Fig. 13-7. Robert Brown.

In 1970, 28 year-old Robert W. Brown joined Foldy, Tobocman, Thaler and Kowalski in the CWRU theoretical particle physics program. Brown was born in St. Paul, Minnesota, completed his BS in physics at the University of Minnesota in 1963, and was awarded his PhD at MIT in 1968. He was a student of John Bronzan. His thesis was entitled the "Comparison of the Scattering of Electrons and Positrons from Protons". **Fig. 13-7.** Before coming to CWRU, he spent two years as a post-doc doing particle theory at Brookhaven. The principal work he performed in that period focused on investigations into "Ward Identity Anomalies". These represented the breaking of classical symmetries by quantum effects.

Brown also expanded upon the work he had done for his Ph.D. degree, the comparison of electron and positron scattering by protons. The leading terms in the expression for the interaction describe an incoming lepton which sees a point target, surrounded by an electric field. Smaller correction terms appear which describe how the internal structure of the proton begins to affect the scattering. He pointed out that data from the SLAC accelerator on e^+p and e^-p small angle elastic scattering were sensitive enough to test his calculations. "Comparison of the scattering of electrons and positrons from protons at small angles" *Phys. Rev.* **D1** 1432 1970.

Intermediate Vector Bosons: $W^{\pm}$ and Z^{o}

Another paper written at Brookhaven in the summer of 1970 was a collaboration with A. K. Mann of U. Pennsylvania and J. Smith of SUNY at Stony Brook. It, too, was directly related to potential accelerator experiments: a comparison between the cross-sections for muon and neutrino induced production of the W boson. The existence of this particle, the proposed mediator of the weak interaction, had been assumed for many years. No one knew what its mass might be, but it was hoped that the energies available at Fermilab would be enough to produce a free W. Brown and his partners calculated cross sections as a function of W mass (1 to 10 GeV) and of incident energy (10 to 1000 GeV), based on the dissociation of the incoming lepton in the Coulomb field of the target proton. They reported that the neutrino induced reaction would be up to five hundred times more probable than the muon induced reaction. "Neutrinos Versus Muons in W-Boson Production" *Phys. Rev. Lett.* **25** 257 1970. It turns out that the W is much more massive than anything that could be produced at Fermilab. It was not discovered until years later, in proton-antiproton collisions at CERN, and it has a mass of 83 GeV.

Over the next two years, Brown, then at CWRU, followed this initial paper with a three-part sequence of longer publications, with Smith and R. H. Hobbs of MIT. The first paper extended the W-production cross-section calculations to interactions of leptons with *nuclei* (rather than just protons). They included corrections for the Pauli principle, for nucleon Fermi motion, for W magnetic moments, etc. The second paper looks at the angular distributions of outgoing muons from these same reactions, assuming prompt decay of the W. The final paper of the series takes up the question of the role of the W (or its neutral counterpart, the Z), as virtual particles, in reactions of the type lepton + nucleus gives three leptons + nucleus. If the available energy in such an interaction is too small to produce a “free” W or Z, the outgoing leptons may still provide some clue of its intervention. (Reactions mediated by the exchange of virtual particles had indeed been observed, and these “off-mass-shell” calculations were all in vogue. Some of the experiments described in Chapter 16, for example, provide evidence for this sort of interaction.) Brown’s papers on the subject: "Intermediate Boson. I. Theoretical Production Cross Sections in High-Energy Neutrino and Muon Experiments" *Phys. Rev.* **D3** 207 1971. "Intermediate Boson. II. Theoretical Muon Spectra in High-Energy Neutrino Experiments" *Phys. Rev.* **D4** 794 1971. "Intermediate Boson. III. Virtual-Boson Effects in Neutrino Trident Production" *Phys. Rev.* **D6** 3273 1972.

Brown also expanded his earlier work on “anomalies” with a paper that cleared up discrepancies in the literature concerning the remarkable fact that there are no higher-order corrections to the original anomaly calculated by Stephen Adler, who along with Young and Wong was his collaborator. “Absence of Second Order Correction to the Triangle Anomaly in Quantum Electrodynamics" *Phys. Rev.* **D4** 348 1971.

Photons and electrons

A strictly electromagnetic interaction, the production of $e^+ e^- e^+ e^-$ by photons incident on virtual photons in the electric field of nuclei, was tackled by Brown and collaborators from Brookhaven and U. Michigan. It was proposed as a way to get at the photon-photon interaction. "Role of $\gamma \gamma \rightarrow e^+ e^- e^+ e^-$ in the High-Energy Cross Section for $\gamma Z \rightarrow Z e^+e^-e^+e^-$" *Phys. Rev. Lett.* **28** 123 1972. A related work on virtual photon processes in e^-e^- or e^-e^+ colliding beams experiments discussed the possibility of measuring the real photon-photon *hadron* production cross sections. "Study of photon-photon interactions via electron-electron and electron-positron colliding beams" *Phys. Rev.* **D4** 1496 1971.

All these papers, calculations of cross-sections from basic principles, were at least in part meant to guide the experimentalist. In fact, the authors often discuss competing backgrounds and other potential drawbacks which would influence the design of an experiment. "Electromagnetic Background in the Search for Neutral Weak Currents via $e^+e^- \rightarrow \mu^+\mu^-$" *Phys. Lett.* **43B** 403 1973. The same considerations were extended to other experiments in other theoretical work. "Non-resonant asymmetry in $e^+e^- \rightarrow \pi^+\pi^-$" *Lett. al Nuovo Cim.* **10** 305 1974. "Possible effects of weakly coupled neutral currents in $pp \rightarrow \ell^+\ell^- + X$" *Nucl. Phys.* **B75** 12 1974.

Work on the production of two electron pairs was extended to higher energies, and for the first time, Brown (with post-doc Karnig O. Mikaelian) would discuss some of the cosmological ramifications of this process. Their calculations showed that at very high energies (10^{21} eV), cosmic photons bouncing along through the cosmic background radiation would disappear in 10^{26} cm or so, or less than a billion light years. "Role of $\gamma\gamma\rightarrow e^+e^-e^+e^-$ in Photoproduction, Colliding Beams, and Cosmic Photon Absorption" *Phys. Rev.* **D8** 3083 1973. "Absorption of High-energy Cosmic Photons through Double-pair Production in Photon-photon Collisions" *Astrophys. Lett.* **14** 203 1973.

Neutral Currents

As experimental evidence for weak "neutral currents" began to become convincing, it seemed that the charged W's mentioned above should be accompanied by an uncharged partner, the Z^o. Neutral currents are required to explain a group of weak interactions in which the participants do not exchange their electric charges. An electrically neutral propagator of the weak field must be exchanged, for example, in elastic scattering of neutrinos by electrons: $\nu e \rightarrow \nu e$. In a series of papers similar to the W papers described above, Brown, Mikaelian (then at U. Penn) and grad-student Leon Gordon presented cross sections for Z production as a function of incident energy (up to 1000 GeV) and Z mass (up to 30 GeV). The first paper looked at collisions with protons. "Production of neutral weak bosons in high energy electron and muon experiments" *Phys. Rev. Lett.* **33** 1119 1974. The next set of calculations looked at Z^o production in the fields of nuclei, and included predictions of polarizations and angular distributions of all out-going particles. "Theoretical spectra and polarization in neutral-weak-boson production" *Phys. Rev.* **D12** 2851 1975. "Theoretical estimates for photoproduction and leptoproduction of neutral vector bosons" *Phys. Rev.* **D13** 1856 1976. Most of this work was done while Brown was on sabbatical at SUNY Stonybrook. As in the case of the W, these calculations are easily extended to higher masses and are appropriate for the experimental mass values. The Z was discovered a decade later and it had a mass of 94 GeV.

This series of papers includes calculations of the expected *cross-sections* for W and Z production. Brown and collaborators consider several possible ways to produce intermediate bosons, each associated with the capabilities of existing or planned accelerator facilities. At that time, the Fermilab accelerator produced 200 GeV proton beams, the Stanford Linear accelerator had colliding beams of 20 GeV electrons, and the Brookhaven proton-proton collider, Isabelle, was on the drawing boards. (The Isabelle project was eventually cancelled). In addition, plans were in the offing for the proton-antiproton machines in CERN and Fermilab.

As the experimentalists were pushing their accelerators and detectors to the limits in an effort to see the carriers of the weak force, Brown *et al.* were providing their best estimates of the cross sections for single W or Z, as well as W^+W^- and Z^oZ^o pair production and, finally, WZ^o and $W\gamma$ production. They considered all available lepton beams and colliding beams. For example, they advise the experimenters that: "It is emphasized that (1) the rate of production of Z^o pairs is comparable to that of W pairs and that (2) W-pair production with colliding proton beams may be the best way to see high-energy cancellations in cross sections, the hallmark of renormalizability in gauge theories." "W^+W^- and Z^oZ^o pair production in e+e-, pp and pbar p colliding beams" *Phys. Rev.* **D19** 922 1979. "$W^{\pm}Z^o$ and $W^{\pm}\gamma$ pair production in νe, pp, and pbar p collisions" *Phys. Rev.* **D20** 1164 1979.

Five years later, after the W and Z had finally been discovered in colliding beams experiments at CERN, Brown returned to the subject with two of his PhD students, Cynthia L. Bilchak and John D. Stroughair. Their goal was to predict angular distributions and polarizations in the various W and Z production channels which would soon be explored at the accelerators. "$W^{\pm}$ and Z^o polarization in pair production: Dominant helicities" *Phys. Rev.* **D29** 375 1984. A decade later, pairs of W's and Z's were produced experimentally. Analysis of these data could set constraints on gauge couplings in the reactions studied by Brown and his collaborators.

A Little Cosmology

Cosmologists have long been intrigued by the fact that the universe seems to have more matter than antimatter and that the galaxies we see today are simply the left-over excess. They have turned to particle physics hoping to identify the source of the asymmetry. An alternate scheme is that there are indeed equal amounts of coexisting matter and antimatter, but they are found in widely separated domains and have not yet had a chance to annihilate. In 1978, Bob Brown teamed up with Floyd W. Stecker, a theoretical astrophysicist at the Laboratory for High Energy Astrophysics at NASA Goddard in Maryland. They had met, through Fred Reines, at a conference on proposed large neutrino detectors. The collaboration of the particle-field-theorist with the cosmic-ray-astrophysicist resulted in a paper which proposed that some of the ideas current in elementary particle theory, such as CP non-conservation and proton decay, could lead one to consider a matter-antimatter *symmetric* universe, but one containing enormous and widely separated domains which are dominated by one form or the other. "We suggest that grand unified field theories with spontaneous symmetry breaking in the very early big bang can lead more naturally to a baryon-symmetric cosmology with a domain structure than to a totally baryon-asymmetric cosmology." "Cosmological Baryon-Number Domain Structure from Symmetry Breaking in Grand Unified Field Theories" *Phys. Rev. Lett*. **43** 315 1979.

Brown and Stecker collaborated once again, this time on a paper which combined Brown's earlier interests in IVB's (intermediate vector bosons, *e.g.* W and Z) with their joint interest in cosmic antimatter. At the time, there were proposals that heavier relatives of the W and Z might exist. The authors suggested that the new and planned very large cosmic neutrino detectors might generate evidence for IVB's too massive to be produced at accelerators. Furthermore, the new detectors could differentiate between incoming neutrinos and anti-neutrinos, thus providing another handle on the question of the amount of antimatter in the universe. "Cosmic-ray-neutrino tests for heavier weak bosons and cosmic antimatter" *Phys. Rev*. **D26** 373 1982.

In the early 1980's, data from experiments at the DESY electron collider in Hamburg indicated a lack of symmetry in the production of muon pairs. In the $e^-e^+ \rightarrow \mu^-\mu^+$ reaction, about 10% more negative μ's came out backward in the center of mass (i.e. opposite the incoming e^-) than came out forward. This reaction provided a nice test of electroweak theory, in that it should be mediated by a mix of photon and Z^o exchange. There had been earlier calculations of the expected asymmetry, but as the data were becoming more precise, it was useful to undertake more detailed theoretical calculations. Brown and two colleagues at the University of Dortmund, R. Decker and E. A. Paschos, refined the calculations and compared the experimental results with the calculated asymmetries. Typical values of the asymmetry were about 10%; their theory agreed with the measurements to about 0.2%. "Weak corrections to the $e^{\pm}e^- \rightarrow \mu^{\pm}\mu^-$ asymmetry" *Phys. Rev. Lett*. **52** 1192 1984.

Predicting Zeros

Most often, theories are developed with the intention of explaining what is observed in experiments. But sometimes the theorist discovers an unexpected feature which jumps out of the theory and which can be tested experimentally. Then, if the effect is observed, the theorist is on the right track. An example is described in a series of papers which Brown coauthored with grad student Deshdeep Sahdev, Mikaelian, Kowalski, and later with S. J. Brodsky of SLAC. The subject is electromagnetic radiation emitted in relativistic collisions. In particular, they noted that interference effects between the incoming and outgoing particle waves give rise to "zeros" in the differential cross-sections. As a result, there are regions in angle and energy where the experimentalist should observe **no** outgoing photons. Because of experimental difficulties and backgrounds (as Brown remarked: "it is hard to see nothing"), it would be many years before the predictions would finally be verified when they were observed in quark-level interactions. "Zeros in amplitudes: gauge theory and radiation interference" *Phys. Rev. Lett.* **49** 966 1982. 'Classical radiations zeros in gauge-theory amplitudes" *Phys. Rev.* **D8** 624 1983; *Phys. Rev.* **D29** 2100 1984.

The subject of these zeros in photon production reappeared ten years later when Brown and his grad student Mary Convery expanded the study to multi-photon production channels. "Radiation tree amplitudes: Zeroing in on more photons and gluons" *Phys. Rev.* **D49** 2290 1994. Meanwhile, theorists at the Brooklyn and Staten Island campuses of the City University of New York had been working on bremsstrahlung (literally "braking radiation"), i.e. photon production in the electromagnetic field of the colliding particles. They were looking at nucleon-nucleon collisions and Brown joined them in a paper on the subject. "Coplanar and non-coplanar nucleon-nucleon bremsstrahlung calculation: A study of pseudoscaler and pseudovector π N couplings" *Phys. Rev.* **C52** R2346 1995.

In the early 1990's, Brown joined forces with Cyrus Taylor (to be introduced in Chapter 18) and research fellow Shmaryu Shvartsman, to look at a problem in quantum field theory. In quantization, there is always a dilemma revolving around whether one has identified all the degrees of freedom, and the associated question of how to quantize each of them. "Role of zero modes in the canonical quantization of heavy-fermion QED in light-cone coordinates" *Phys. Rev.* **D48** 5873 1993.

Solitons, Strings and Undergrads

Bob Brown is, certainly among the theorists in the department, the one who has most often involved undergraduate physics students in research. For many years, he has taught the immensely popular "honors" course for freshman, an introductory course into which he inserts exciting topics in modern theoretical physics. Each student in the course participates in projects, many computer-based, which illustrate cutting-edge applications of the physics taught in the usual introductory course. In addition, Brown has regularly worked with the senior majors in helping them organize their preparation for their GRE's (graduate record exams) and their selection of and application to graduate school. These interactions with undergrads have often led to collaborative published work in which the students were major players.

In the 1980's, undergraduate students joined Brown in making discoveries in classical nonlinear physics. The first, with one undergraduate and two graduate student co-workers, addressed proving the full stability of underwater solitary waves in the presence of large (nonlinear) disturbances. The second concerned research on cosmic strings. These hypothetical huge, massive, but vanishingly thin strands, stemming from phase transitions in the early universe, may account for some features of galaxy formation. In one paper Brown and his grad student David DeLaney reported their discovery of a convenient way to represent the Fourier series for a vector which promised to be useful in string theory. "Product representation for the harmonic series of a unit vector: A string application" *Phys. Rev. Lett.* **63** 474 1989.

A sophomore undergraduate joined Brown in a general mathematical formulation of this solution, and another, even younger undergraduate worked with Cyrus Taylor and Brown in presenting an elegant spinor representation of the general harmonic string solution. Additional solutions were also studied featuring kinks representing intersections of strings with each other or with themselves. "Closed strings with low harmonics and kinks" with M.E. Convery, S.A. Hotes, M.G. Knepley, and L.S. Petropoulos *Phys. Rev.* **D48** 2548 1993.

In 2004, Brown was recognized for his dedication and originality in the teaching of undergraduate physics by being awarded the national AAPT (American Association of Physics Teachers) Excellence in Introductory College Physics Teaching Award. From the department website: "This is the highest award given for introductory physics teaching in the country. This award reflects the incredible job Bob has done over the past decades in innovative teaching, including using the web well before anyone else and developing peer teaching techniques, as well as inspiring scores of undergraduate students to excel." In 2005, Brown won the equally prestigious Cherry National Teaching Award.

A Problem in Jackson

Bob Brown has taught the graduate course on the theory of electromagnetism many times over. This is one of the few absolutely required courses for PhD students, pretty much worldwide. And the textbook first written by J. D. Jackson in 1962 continues to be "*the* authority". A wonderful feature of "Jackson" is the many problems it includes, problems which have challenged grad students (and their teachers) for two generations.

In 1991, Brown, three of his graduate students, Mike Martens, Labros Petropoulos, Jim Andrews, and two former students, M.A. Morich and John Patrick, published a paper on the design of a magnet system which qualified as a rather advanced "Jackson problem". This paper would mark the beginning of a new and different line of research for Brown. In it, the authors describe a technique for calculating the spatial distribution of electric currents which would produce the optimum magnetic fields for a medical imaging device, an "inverse problem". The application of classical electromagnetic theory to the technology of magnetic resonance imaging is a far cry from theoretical quantum particle physics. Brown's entry into the field of medical imaging follows by a hundred years the pioneering x-ray work of Dayton Miller described in Chapter 4. At the same time as Brown's MRI work, Bill Tobocman was developing a parallel program in the application of scattering theory to medical ultrasound imaging (Chapter 9).

An aside on the physics of nuclear magnetic resonance imaging *(now called MRI, because the* Nuclear *part of NMR was scaring people away). The object of the game is to determine how many hydrogen atoms there are in a given region of space and what their environment is - without touching them. This information can be used to learn about the interiors of biological systems without cutting into them. The physics of the game is based on what happens to the proton nucleus of the hydrogen atom when it finds itself in a magnetic field. This is the only place where "non-classical" physics comes in. Quantum mechanically, the proton has an intrinsic spin and an associated magnetic di-*

pole moment. If the proton is sitting in an external magnetic field, B_o, and the proton spin is "tipped over" by a short magnetic pulse, its magnetic moment will precess with a specific frequency f_o around the direction of B_o. Quantitatively, the proton precession frequency f_o in MHz equals 42.6 times B_o in Tesla. The precession gives rise to a changing magnetic field which can be detected. That's the end of the physics.

Now the trick of MRI: if one puts a gradient on B_o, that is, B_o varies smoothly along one dimension in the sample, the frequency of the detected signal will depend on where the protons are. Thus one can identify which slice of the sample the signal is coming from. This insight led to the explosion of MRI applications described almost daily in the news media and the Nobel Prize in Medicine for the inventors of the gradient-field idea in the Fall of 2003.

Now the technology: one must design coils to produce the fields (for B_o, for the gradient ΔB_o, and for the short excitation pulse) and the receiver coils to detect the precession signal.

Some details: it turns out that the room temperature thermal energy is far greater than the energy associated with the precessing protons, but there are so many protons involved that a measurable signal survives. The rate of precession depends slightly on the environment surrounding the proton because of interactions with neighboring atoms. Furthermore, the rate at which the precession signal decays also depends on the environment. Consequently, frequency and time-dependent amplitude measurements provide additional useful information. The bottom line: one can learn where the protons are (in three dimensions), and what their chemical environment is.

The 1991 paper by Brown and his students was on the design of the coils which produce the gradient, ΔB_o , for an MRI scanner, but with minimized inductance. It is desirable to reduce coil inertia in order to be able to turn such coils on and off as rapidly as possible, and thereby speed up the imaging process. **Fig. 13-8** shows the calculated spatial distribution of the currents. The group actually built a ½-scale model, with all the wires held in position on a plywood sheet. They then measured the resulting B field in the region where the imaging would be done. **Fig. 13-9** shows the comparison between the calculated and measured fields. The agreement was better than 5%. Two of the authors were already employed by Picker International which is now owned by Philips, which, along with General Electric and Siemens, is a leader in MRI technology. "Insertable biplanar gradient coil for MR imaging," *Rev. Sci. Instr.* **62** 2639 1991. Two years later, the same authors would tackle another geometry, one especially relevant to the human

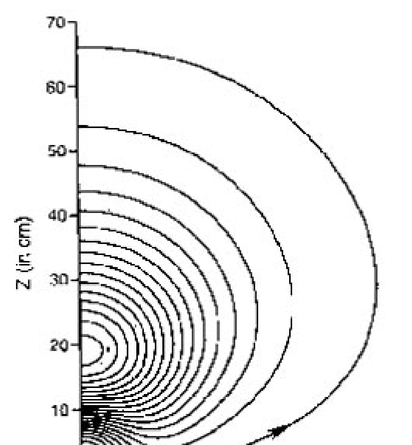

Fig. 13-8. Current directions in two dimensional model of an MRI gradient coil..

profile. "An MRI elliptical coil with minimum inductance," *Meas. Sci. and Tech.* **4** 349 1993.

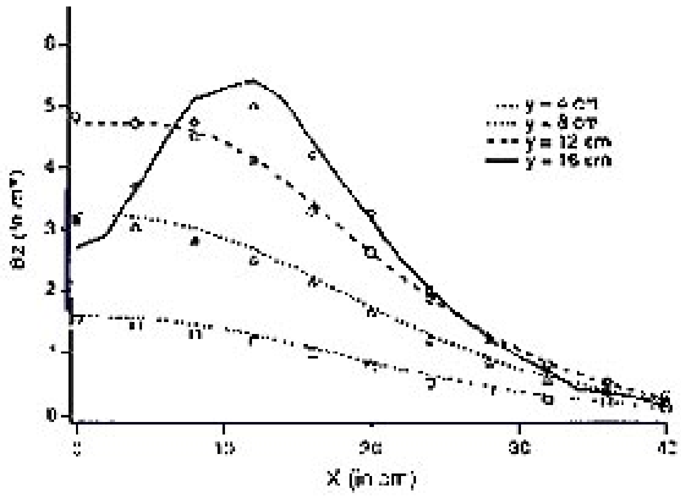

Fig. 13-9. Comparison between calculated and measured fields in MRI model configuration.

Brown and his group continued to improve upon the design of MRI magnet coils, with various goals in mind. Among these are uniform gradients to allow high resolution, low inductance to enhance quick response, large openings to allow easy access, and shielding coils to reduce stray fields outside the device. The group also moved into related MRI computational electromagnetics analysis in the design of the main magnets that produce the large Tesla-level field and the rf coils which detect the proton spin fields. A new short-coil design with a paradigm shift to include a central bundle of wires was found. "An inverse approach to the design of MRI main magnets," *IEEE Trans. Mag.* **30** 108 1994. The same "inverse" procedure used in gradient design was applied to rf coil development in a later paper. "A hybrid inverse approach to the design of lumped-element rf coils," *IEEE Trans. Biomed. Eng.*,. **46** 353 1999.

The team also modeled the *temperature* distribution in surrounding tissue in medical procedures where MR-guided rf probes are used for ablating tumors. Good agreement was found between the simulations and the measured ablation volume in comparisons with clinical work carried out at the neighboring University Hospitals. "Calculated rf electric field and temperature distributions in rf thermal ablations: comparison with gel experiments and liver imaging," *JMRI* **8** 70 1998.

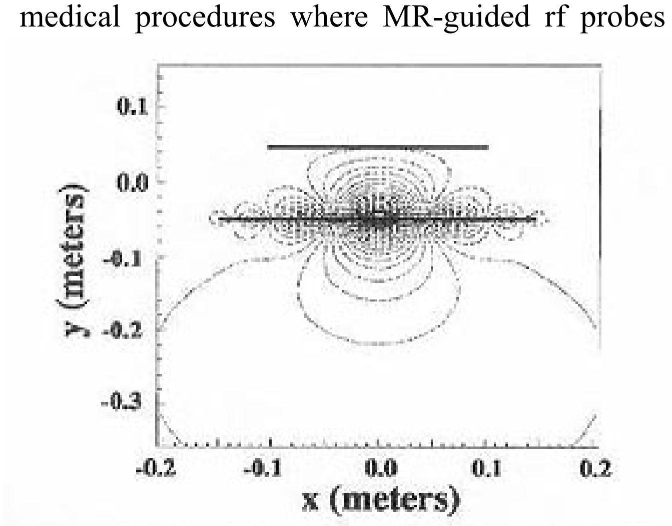

Fig. 13-10. Magnetic field lines confined by supershielding. Note the absence of field above the upper current sheet.

In 1999, Brown and his colleague, research fellow Shmaryu Shvartsman, published a paper titled: "Supershielding: Confinement of Magnetic Fields". *Phys. Rev. Lett.* **83** 1946 1999. The fact that the paper was published in a flagship AIP journal rather than in a technical MRI or medical journal indicates that the topic is of general interest to physicists, in the J. D. Jackson spirit. The work develops a theoretical limit on how good the shielding can be for open MRI coils. Shielding is essential to kill the production of eddy currents in the surrounding main magnet. The field due to these currents degrades the image and the currents themselves experience a Lorentz force from the main field that leads to additional noise. In this classic paper, a "shielding error function" is defined and an equation is given for it. The succinct result is that minimizing this function guarantees the best shielding available, subject to other constraints and design goals.

The technique described in the paper is based on the placement of two strips of conductors, each divided into narrow sub-strips, each of which carries a specified amount of current. **Figs. 13-10** shows how the appropriate current distributions can reduce the field above the upper strip to zero. **Fig. 13-11** shows the current distributions in the upper and lower strips which result in the shielded field.

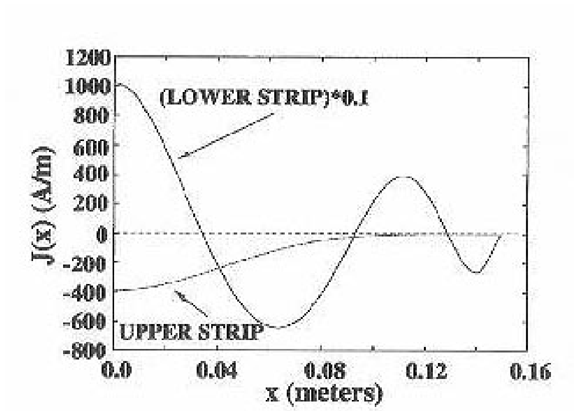

Fig. 13-11. Current distributions in the two strips in a SUSHI system.

A large effort with a correspondingly large group of graduate students and faculty continues to be made in follow-up work that has led to smaller and smaller error functions and thus better and better shielding in the standard MR system. "Application of the SUSHI method to the design of gradient coils" *Mag. Res. Med.* **45** 147 2001 and *IEEE Trans. Mag.* **37** 3116 2001. (This tasty contraction of SUper-SHIelding is easy to remember.)

In 1999, Brown and his longtime collaborator, Mark Haacke, and their former students, Mike Thompson, and R. Venkatesan, published a comprehensive book on the subject of MRI. They describe the book as a text for a two-semester course for graduate students or advanced undergrads in physics or engineering. The 914-page book includes chapters on the related physics, mathematics, biology, and engineering. The 27th and last chapter is an introduction to MRI coils and magnets. This is where the Jackson – and Morse and Feshbach – influence can be found. The text has been described variously as the "green MRI bible" and the "daily companion of the MRI scientist," by researchers in the field. "Magnetic Resonance Imaging: Physical Principles and Sequence Design", E. Mark Haacke (Washington University), R. W. Brown, M.R. Thompson (Picker International), and Ramesh Venkatesan (GE Medical Systems, Bangalore), 914 pp., John Wiley & Sons, New York 1999.

A problem in topology and another in fluid analysis

Visitors often come to the Rockefeller building with a question which a physicist may or may not be able to answer. One such visitor was a surgeon from nearby University Hospitals who was seeking advice on how to make quantitative and reproducible measurements of surgical modifications. Specifically, she wanted to know what easily measured parameters would allow one to determine the volume of a woman's breast, before and after surgery. She was referred (by your author) to Bob Brown who had experience with MRI and the associated measurements on patients. The meeting led eventually to a paper coauthored with post-doc Y. C. Norman Cheng and the surgeon, M. Kurtay. "A Formula for Surgical Modifications of the Breast" *Plastic and Reconstructive Surgery* **106** 1342 2000.

Another of Brown's contributions to technology involved work done with departmental lab director Bill Condit, colleague Don Schuele, Norman Cheng, and several students. The challenge was to develop an easy way to quantify the level of contamination of lubricating oils by wear particles and other impurities. The solution was based on the measurement of the capacitance of a capacitor cup filled with the oil. Recall that Schuele is an expert at such measurements as described in Chapter 12. The measured effective dielectric constant can be related to the concentration of impurities. Furthermore, the application of a voltage to the capacitor can be used to produce current discharges. The critical voltage for these is related to the amount of iron wear particles.

A summary, of sorts

The following are two excerpts from the description of Brown's teaching and research which appears on the department website.

"My basic research has been supported by the NSF for 20 years, including REU (Research Experience for Undergraduates) awards for 26 undergraduates, 15 published papers in which the students were authors or coauthors, and 12 NSF graduate fellowships. There have been 15 Ph.D.s under my advisory."

"In much of the applied research, I have worked for a number of years in the search for ways in which elegant and powerful mathematical tools can be used to solve practical problems, tools such as variational calculus with constraints. … This is analogous to field theory work in basic particle theory. Our problem-solving group, consisting of students and faculty, has worked out a large number of designs that have led to publications, industrial products, and … patents. The emerging lesson is that more and more products in the business world, including financial investment instruments, can be effectively mathematically modeled and their qualities thereby mathematically optimized."