that increases the risk of magnet quenching. However, a fast extracted beam is needed for neutrino experiments, scheduled to start next year.

The proton–antiproton collider project is well underway, according to John Peoples, who heads the project. The old main ring will receive a batch of protons from the old booster, accelerate it to 120 GeV, compress the batch in time and then the protons will hit a target to produce antiprotons.

Every 2 seconds the target is expected to yield 8×10^7 antiprotons. These are sent to two rings—first a debuncher and then an accumulator. Although the CERN collider at present has only an accumulator, CERN plans to add a debuncher called the Antiproton Collector. The Fermilab debuncher allows a much larger momentum spread initially so that more antiprotons can be collected in the end. However, Peoples points out, two rings take longer to make and are more complicated. By stochastic cooling, the debuncher is expected to reduce beam emittance in both transverse planes by a factor of three in 2 sec. Then the antiprotons will be transferred to the accumulator, where stochastic cooling is to be done in the longitudinal plane. After 10 000 pulses of the Tevatron, the experimenters expect to stack 6×10^{11} particles in the accumulator. So in two hours, Peoples says, "we should have enough antiprotons to do colliding beams: 2×10^{11} antiprotons."

To produce collisions, 2×10^{11} antiprotons will be removed from the accumulator and injected into the main ring, accelerated to 150 GeV and injected into the Tevatron as three bunches traveling counterclockwise. Earlier, three bunches of protons will have been accelerated in the main ring and injected clockwise into the Tevatron. Both particle beams will then be simultaneously accelerated close to 1 TeV and stored. For a long beam lifetime, Fermilab will need a very reliable Tevatron.

Fermilab's goal is to accumulate enough antiprotons to allow a low-luminosity test of $p\bar{p}$ collisions in June 1985. At that time, Peoples hopes that with only a single bunch of protons and a single bunch of antiprotons, the machine luminosity will exceed 10^{28} $cm^{-2}sec^{-1}$; the Collider Detector Facility also is expected to have a shakedown run then.

CDF, the first of two detectors for the $p\bar{p}$ collider, is under construction at Fermilab and other locations. Roy Schwitters (Harvard) and Tollestrup are spokesmen for the detector collaboration, which has about 140 individual participants; the device will cost \$40 million. A second detector (whose cost is about \$25 million), to be placed in the D0 region of the collider, has not yet been approved by DOE, but the physics itself has been approved by Fermilab. Spokesman for the D0 collaboration is Paul Grannis (Stony Brook). Both detectors are about the size of UA1 and UA2 at the CERN collider and more complex than UA1. The collision hall for CDF has been finished and the construction of the D0 area will begin in 1985, after the first $p\bar{p}$ collisions occur. The shutdown for the D0 area would end February 1986. By summer or fall of that year, Peoples hopes the first physics run with $p\bar{p}$ collisions will occur. —GBL

Relativistic treatment of low-energy nuclear phenomena

Because the binding energies of nuclei are very much smaller than their rest masses, one would not have expected relativistic effects to play a significant role in nuclear structure or nuclear scattering at modest energies. Thus the nonrelativistic Schrödinger equation has until recently been the basis for almost all calculations in traditional nuclear physics. But in the past three years, the coming together of precise new data and novel theoretical approaches has made it appear that a fully relativistic treatment is indispensable for the understanding of nuclear phenomena even at low energies.

In 1981, new capabilities at the Los Alamos Meson Physics Facility made it possible for the first time to measure in essentially complete detail the elastic scattering of polarized protons off spin-zero nuclei at energies where the free nucleon–nucleon scattering amplitudes are well known (up to 500 MeV). At these energies, one expected the elastic scattering to be well described by the impulse approximation, which calculates a complex "optical" scattering potential for the nucleus as a whole on the assumption that the incident proton is scattered by quasifree individual protons and neutrons in the nucleus, neglecting binding energies and other effects of the nuclear medium. The impulse approximation has been an important tool in the ongoing effort to understand nuclear phenomena in terms of the two-body interactions of their constituents.

The new Los Alamos data, however, didn't seem to fit this generally accepted picture. Calculating the impulse approximation from the known free-nucleon amplitudes in the conventional nonrelativistic Schrödinger-equation formalism, the experimental groups found that they could not reproduce the three experimental functions that together give a complete description of the elastic scattering of polarized protons off spinless nuclei: the differential cross section, the left–right asymmetry as a function of scattering angle (called the analyzing power) and the spin-rotation function (which requires a determination of the spin orientation of the proton *after* the scattering). This *apparent* breakdown of the impulse approximation had not been noticed before 1981 because spin-rotation data were very sparse and because LAMPF was only providing proton beams at 800 MeV, where the free proton–neutron amplitudes are poorly known. The impulse-approximation calculations essentially involve no free parameters, but the incompleteness of the earlier data had introduced sufficient latitude to permit plausible fits.

The first of these 1981 experimental papers[1], describing the differential cross sections and analyzing power of 500-MeV protons scattered off various nuclear species by a University of Texas–Northwestern collaboration, speaks of "the breakdown of the impulse approximation." "We are forced to consider the possibility of a ... fundamental theoretical inadequacy ... in the conventional application of the ... formalism." The inadequacy, the authors suggest, is the intrinsic failure of the impulse approximation to take sufficient account of the collective modifying effect of the nuclear medium on the quasi-two-body collisions. They believed they were seeing a significant and unexpected difference between free nucleon scattering and what happens inside a nucleus.

Schrödinger formalism. It now appears that the fault lay not in the impulse approximation, but rather in the Schrödinger equation itself. The Schrödinger equation is of course a nonrelativistic approximation to the real world, where the Dirac equation is presumed to provide a relativistically correct description of the scattering of protons and neutrons. Although the energies in question here are not very relativistic and the trivial effects of relativistic kinematics have always been taken into account at intermediate energies, the crucial issue that requires the relativistic treatment appears to be the spin dependence of the nucleon–nucleon interaction. Spin is, after all, an intrinsically relativistic phenomenon. Historically, the first great triumph of the Dirac equation was its explanation of the spin and magnetic moment of the electron.

The large spin-dependent effects observed in proton–nucleus scattering are now thought to result from the fact that the relatively shallow effective nuclear potential (about 50 MeV deep) is the net result of a near cancellation between much larger covariant potential terms. Because these underlying potentials have magnitudes on the order of the nucleon mass, a relativistic treatment appears inescapable.

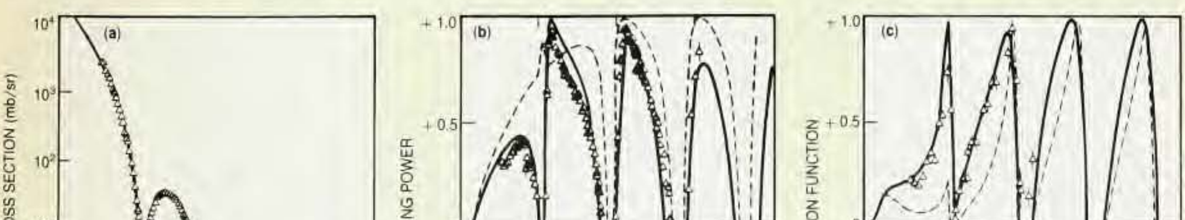
In the traditional Schrödinger formalism for the impulse approximation, one translates the empirically known nucleon–nucleon phase shifts at a given collision energy into the various nonrelativistic Pauli scattering amplitudes: nonflip, spin-flip and double-spin-flip. These Pauli amplitudes are then folded together (by a convolution integral) with a plausible density function describing the spatial distribution of nucleons in the nucleus. This folding of the two-body scattering amplitude with the density distribution yields the complex nuclear optical potential with which one solves the Schrödinger equation to predict the differential cross section, the analyzing power and the spin-rotation function. In this nonrelativistic formalism, the nuclear potential has two terms—a central potential and a spin–orbit coupling potential.

Even before the 1981 LAMPF data there was some motivation to treat intermediate-energy proton–nucleus scattering relativistically. In phenomenological applications of the Schrödinger formalism to scattering data above 200 MeV, the spin–orbit part of the nuclear optical potential exhibited a rather complicated and unnatural energy dependence. Furthermore, the spatial distribution of the central potential turned out to have a peculiar, "wine-bottle-bottom" shape that seemed to bear no relation to the real distribution of nucleons in the nucleus.

The depths of the optical potential wells deduced from the nonrelativistic formalism also presented a problem: In the early 1970s there had been attempts at understanding the structure of nuclei by approximations to a relativistic, many-body quantum field theory involving the exchange of scalar and vector mesons. These calculations suggested that the saturation of nuclear density—the puzzling fact that nuclei don't collapse to ever higher densities as more nucleons are added—is due to a balancing between a large repulsive vector potential and a large attractive scalar potential that decreases with increasing nuclear density. These covariant potentials turn out to be an order of magnitude larger than the potential terms one gets from nonrelativistic fits to the scattering data. The decrease of the attractive scalar potential with increasing nuclear density is a purely relativistic effect, to be contrasted with the traditional explanation that attributes saturation to repulsive "hard cores."

Dirac phenomenology. Since the early 1970s Bunny Clark (Ohio State) and a number of collaborators have been doing phenomenological fits to proton–nucleus scattering data in a relativistic formalism that employs covariant optical potential terms in the Dirac equation. Rather than calculating the nuclear optical potentials from known nucleon–nucleon scattering amplitudes as one does in the impulse approximation, this phenomenological approach determines the potentials by fitting about a dozen free parameters to the scattering data. The analogous nonrelativistic procedure, using the Schrödinger equation with a Pauli representation of the spin–orbit potential term, has been widely used for the phenomenological analysis of nuclear-scattering data. There was, in fact, considerable skepticism about the necessity for a relativistic treatment.

Clark's analysis of the 1981 LAMPF data made converts to the Dirac formalism. At a workshop on the interaction of medium-energy nucleons in nuclei, held at Indiana University in the fall of 1982, she reported[2] that she and her colleagues, Shinichi Hama (Ohio State) and Robert Mercer (IBM), had been able to achieve excellent phenomenological fits to the LAMPF 500-MeV cross-section and analyzing-power data where the nonrelativistic approach has failed. But what really made people sit up and take notice was the ability of these fits to *predict* with startling accuracy the spin–rotation functions, which had become available[3] only after a new focal-plane polarimeter, capable of yielding double-scattering measurements, had been installed at LAMPF. Once again, the corresponding predictions from nonrelativistic fits were badly off the mark. A year earlier Clark, Mercer, Louis Arnold (Ohio State) and Peter Schwandt (Indiana) had attracted attention by explaining away the wine-bottle anomaly in lower-energy scattering data as an artifact introduced by forcing the Schrödinger equation, which suppresses negative-energy states, on potentials that show them-



The relativistic impulse approximation developed by McNeil, Shepard and Wallace, and numerically computed by Clark and her collaborators [Phys. Rev. Lett. **50**, 1644 (1983)] *without fitting any free parameters* (solid curves), shows excellent agreement with the LAMPF data (triangles) for 497-MeV polarized protons elastically scattered off calcium-40 nuclei. For the differential cross section (**a**), the traditional Schrödinger-equation formalism yields an inferior, but not disastrous, fit (dashed curves.) For the spin-dependent data, however, this *nonrelativistic impulse approximation does badly: Figure* **b** shows the analyzing power, that is, the left–right asymmetry in the plane normal to the beam polarization, and **c** shows the spin-rotation function, which was measured on the focal-plane polarimeter at LAMPF.

selves perfectly well behaved in the Dirac formalism, which takes the negative-energy states properly into account.

In the Dirac formalism the central and spin–orbit terms of the nuclear optical potential are replaced by potentials with explicit Lorentz transformation properties: scalar, vector, tensor, pseudoscalar and axial vector. (The last two are prevented by parity conservation from contributing to elastic scattering off spinless nuclei, and the tensor potential is small enough to be neglected.) A central problem of nuclear physics, of course, has been the absence of a definitive theory, analogous to quantum electrodynamics, which would give us the Lorentz character of the hadronic interaction. In the phenomenological approach, the relative strengths and phases of the scalar and vector potentials must come from fits to the scattering data. Whereas the nonrelativistic phenomenology yields potential wells only about 50 MeV deep, Clark's fits describe this shallow effective potential in terms of a competition between much larger (about 400 MeV) scalar and vector potentials—very much like the conclusion reached by the earlier field-theoretical calculations. The imaginary part of the scalar potential turns out to be positive, corresponding to particle production, while the negative imaginary part of the vector potential accounts for absorption.

Relativistic impulse approximation. How does one decide whether the potentials deduced from these phenomenological fits with a fistful of adjustable parameters have any serious relation to reality? One can attempt theoretical calculations of the nuclear potential from first principles, or one can undertake a relativistically correct impulse-approximation calculation with the empirically known free nucleon–nucleon phase shifts as input. The latter approach was taken by James McNeil (Villanova), James Shepard (University of Colorado) and Stephen Wallace (University of Maryland) after hearing Clark's talk at the Indiana workshop. Wallace told us that he had earlier been skeptical because the positive sign of the imaginary part of Clark's scalar potential in the winebottle fits didn't seem to make sense, and more generally because "you can fit almost anything with enough free parameters." But the correct prediction of the first spin-rotation-function data began to undermine his doubts.

Wallace and McNeil had previously worked out the formalism for computing the free nucleon–nucleon amplitudes from the phase-shift data in the invariant Dirac representation. McNeil, Shepard and Wallace went home from Indiana and developed the relativistic formalism for folding these two-body amplitudes with the nuclear density distribution to get the relativistic nuclear optical potential with which one solves the Dirac equation for proton–nucleus scattering. "To our surprise," Wallace told us, the resulting nuclear potentials[4], calculated *without* free parameters, were essentially the same as those found by Clark's phenomenological fits. She had, among other things, been right about the signs of the imaginary parts.

More recently, Clark's group has teamed up with Brian Serot (Indiana) and Lanny Ray and Gerald Hoffmann (both at the University of Texas) to undertake a detailed and systematic program of numerical computation of proton–nucleus scattering using the relativistic impulse-approximation formalism of McNeil and company.[5] Ray and Hoffmann, who had done extensive data fitting in the Schrödinger formalism, bring to this collaboration an elaborate computer code for folding the free-particle scattering amplitudes with the nuclear density. Serot is contributing better relativistic estimates of the nuclear density distribution, which he and Charles Horowitz (MIT) are trying to understand[6] by refinements of the earlier relativistic field-theoretic approximations.

Underlying theory. Even though the relativistic impulse approximation appears to give an excellent description of proton–nucleus scattering at intermediate energies without any free parameters, it is still basically an empirical recipe applicable only at bombarding energies above about 200 MeV, using the experimental free-nucleon scattering amplitudes as its input. One would like to understand nuclear phenomena at a more fundamental level.

The problem of nuclear scattering at modest energies is closely related to that of nuclear structure. The essential difference is the sign of the energy in the wave equation. Almost thirty years ago Hans Peter Duerr (then at Berkeley) made a pioneering attempt at analyzing relativistic effects in the nucleus. But the mesons that now appear to play a crucial role in mediating the nuclear force were not yet known. In 1971 Dudley Miller and Alex Green at the University of Florida developed the formalism for a relativistic meson-exchange field theory of nuclear structure—a first attempt to do the nuclear shell model relativistically. Two years later Dirk Walecka at Stanford did much the same thing for infinite nuclear matter; he was particularly interested in neutron stars. Both approaches employed simplifying mean-field approximations—replacing the quantum-fluctuating meson fields by their classical expectation values. This approximation expedites solution of the quantum field theory, but it forces one to ignore short-range nucleon–nucleon correlations that are probably important in strongly interacting nuclear matter. Walecka concluded, as had Miller and Green, that one can understand nuclear density saturation in terms of a large, repulsive vector-meson-exchange potential balancing an attractive scalar-meson exchange that weakens relativistically with increasing nuclear density.

These mean-field-approximation theories of the early 1970s still retained a certain phenomenological character. To fit the known properties of nuclear matter, the theorists found it necessary to treat the meson-exchange coupling constants as free parameters. Trying to fit nuclear matter with meson couplings known from low-energy, free nucleon–nucleon interaction gave the wrong answer. In retrospect the problem appears to have been the neglect of correlations in the mean-field approximations.

Carl Shakin and his colleagues at Brooklyn College, having found a way around the mean-field approximation, believe they have now solved the problem.[7] They employ a relativistic Brueckner–Hartree–Fock approach—summing an infinite series of meson-exchange ladder diagrams—to solve the relativistic, many-body quantum field theory without free parameters. Because this technique takes proper account of nucleon–nucleon correlations, Shakin told us, they are able to describe nuclear density saturation as well as proton–nucleus scattering from the lowest energies (where the impulse approximation fails) all the way up to 1 GeV in terms of the known, low-energy, free nucleon–nucleon meson-exchange potentials. Their results are similar to those of Serot and Horowitz, and they reproduce well the relativistic phenomenological fits of Clark and her colleagues. —BMS

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