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NUCLEON–NUCLEON SCATTERING

An atomic nucleus can be considered a set of two-nucleon systems.
What are the forces between these pairs?
How do protons and neutrons differ and how are they similar?
Studies during the past three decades have given some answers and indicated which new kinds of experiments are likely to be most useful.

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DETERMINATION OF THE fundamental law of force between two nucleons has occupied many physicists for the past three decades. Because the proton and electron have obvious similarities (elementarity, spin of 1/2, equal but opposite electric charge, Fermi statistics, antiparticles) the derivation of a nuclear "Coulomb's law" would seem to be a just reward for working in this area. As we have rather slowly and laboriously learned, however, simplicity appears to be inversely proportional to some power of the coupling constant.

Indirect means can be used to learn about the forces between two nucleons. An atomic nucleus, composed of protons and neutrons, can be reasonably treated as a collection of interacting two-nucleon systems. From the overall behavior of the nucleus, certain properties of the nuclear force, such as its range and the statistics it obeys, can be adduced. Direct information, however, is obtained only by scattering one nucleon off another. Analysis of these scatterings will be the subject of the present discussion.

Early history

The most distinctive feature of the nuclear force, its very short range, was deduced by Ernest Rutherford in 1911. Modern studies of nucleon–nucleon interaction were initiated in 1932 when the neutron was discovered[1] and high-voltage particle accelerators first produced nuclear reactions.[2] Some of the most crucial discoveries were made very early, as often happens. By studying the binding energy of the alpha-particle Eugene Wigner[3] in 1933 confirmed that nuclear forces have a short range and are very strong. Werner Heisenberg[4] and Ettore Majorana[5] pointed to the repulsive-core concept when they invoked exchange forces to explain the stability of nuclei against collapse. In 1935 Hideki Yukawa[6] predicted that the nuclear force should be mediated by exchange of a virtual meson with a mass of roughly 100 MeV.

Nucleon–nucleon scattering occurs within the constraints imposed by invariance under time reversal and conservation of angular momentum and parity. For a given total angular momentum **J** the proton–proton system has five independent ways in which the intrinsic spins and the orbital angular momentum can couple together. These alternatives are shown in figure 1. The two possibilities listed as amplitude 5 in figure 1 are equivalent; one is the time-reverse of the other, and we are assuming time-reversal invariance. The antisymmetry of the proton–proton wave function when combined with the conservation of angular momentum and parity prevents mixing of singlet ($S = 0$) and triplet ($S = 1$) spin states.

If we assume that the proton and neutron are isotopic states of the same particle that differ only in the $I_z = \pm 1/2$ projections of their isotopic spin, then the neutron–proton wave function must be antisymmetric. In this case, we have the same five scattering amplitudes in spin space as we did for proton–proton scattering. Scattering, however, now occurs in two isotopic spin states ($I = 1$ and $I = 0$); so the direct product gives ten independent neutron–proton scattering amplitudes. The $I = 1$ amplitudes as measured in proton–proton and neutron–proton scattering should be identical in all but electromagnetic effects. This is

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the *charge independence* hypothesis. The weaker *charge-symmetry* hypothesis specifies that, apart from electromagnetic effects, proton–proton and neutron–neutron forces are equal.

Nonconservation of isotopic spin is indicated by the unequal masses of charged and neutral pions and of the proton and neutron, the nonlinearity inherent in superimposing nuclear and electromagnetic forces and the differing anomalous magnetic moments of proton and neutron. Fortunately for us here, these are all rather small effects. Assumption of charge independence is, we shall see, indispensible for analysis of existing neutron–proton scattering data.

Because nucleon–nucleon scattering occurs simultaneously in five independent spin states, it is necessary to analyze five kinds of scattering experiments at a given energy simultaneously to determine the elastic-scattering matrix at that energy. This fact makes a definitive experimental determination of the scattering amplitudes a formidable task.

Observed spin and isospin dependence

Observations pointing both to the greatest complication in the nuclear force and to its greatest simplification occurred in 1936. The deuteron is a neutron and proton bound in a triplet spin state. From the deuteron structure we can infer the cross-section magnitude for triplet neutron–proton scattering at zero energy. The observed neutron-proton scattering, which is 1/4 in the singlet state and 3/4 in the triplet state, is much larger than this value. Thus, as Wigner[7] pointed out, singlet neutron–proton scattering must be much larger than triplet neutron–proton scattering; this work established that nuclear forces, unlike simple Coulomb forces, are spin dependent.

Further evidence for spin dependence of the nuclear force was soon forthcoming. In 1939, measurements of the magnetic moment and electric quadrupole moment of the deuteron[8] showed that tensor forces, leading to a D-state admixture in the S-wave ground state, are present. Analysis of high-energy proton–proton scattering data by Kenneth Case and Abraham Pais[9] in 1950 showed that spin-orbit components are also present in the nuclear force. The conclusion that we have today, which is borne out by studies with a variety of potential models, is that nature has taken full advantage of the freedom in nucleon–nucleon spin space afforded by the invariance principles; spin dependence of nuclear force is as complicated as it is allowed to be.

The greatest and perhaps only simplicity in nucleon–nucleon scattering occurs in isotopic-spin space. In 1936, Gregory Breit and Eugene Feenberg[10] analyzed low-energy neutron–proton and proton–proton scattering and showed that the singlet-S nuclear phase shift (the $I = 1$ scattering) is the same for both processes to within a few percent, thus experimentally establishing charge independence. Many subsequent experiments during the past third of a century have substantiated the usefulness of the charge-independence approximation. It is interesting that Breit and coworkers[11] in 1968 were the first to introduce a nucleon–nucleon phase-shift analysis in which charge independence is no longer strictly assumed. Breit's work in nucleon–nucleon interactions has spanned the entire modern development of the subject (see figure 2).

GREGORY BREIT (left) and EUGENE WIGNER. This famous resonance is shown at the Gainesville, Florida international nucleon–nucleon conference in 1967. —FIG. 2

Amplitude	Spin S	Orbital Angular Momentum l: Initial	Final
1	0	$l = J$	$l = J$
2	1	$l = J$	$l = J$
3	1	$l = J + 1$	$l = J + 1$
4	1	$l = J - 1$	$l = J - 1$
5	1	$l = J \pm 1$	$l = J \mp 1$

SPIN-SPACE NUCLEON–NUCLEON amplitudes for total angular momentum J. Intrinsic spin and orbital angular momentum can couple in five ways. —FIG. 1

Nucleon–nucleon amplitudes

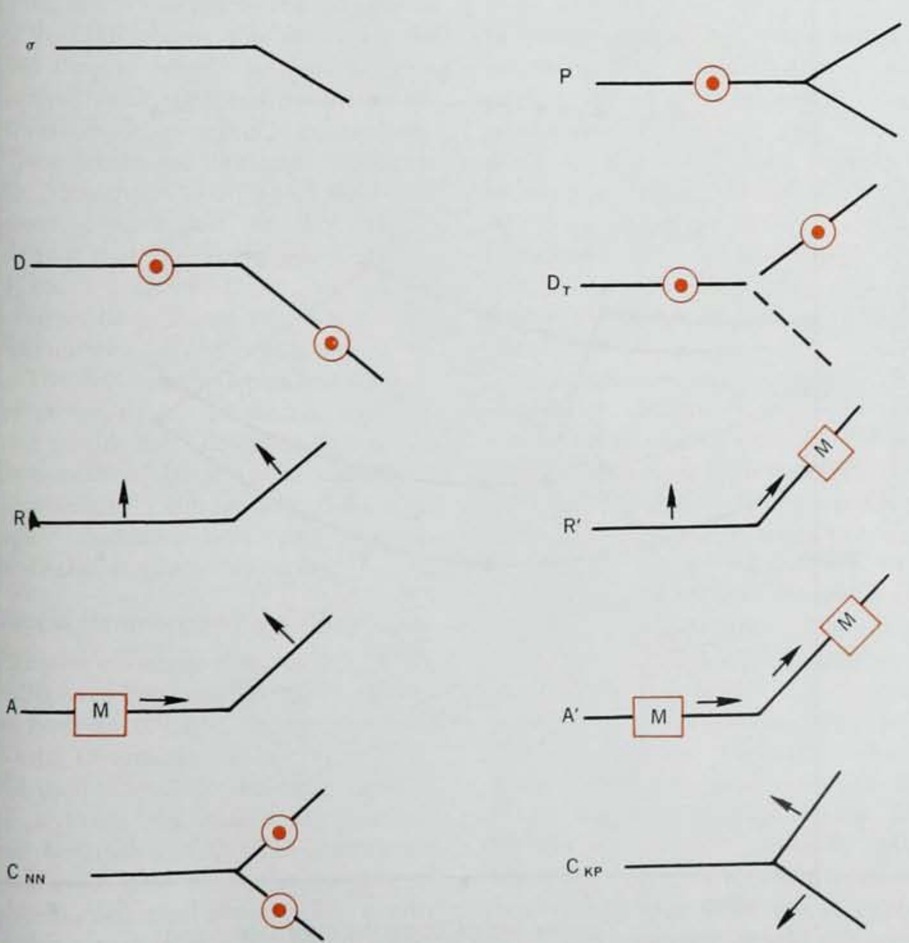
As we have seen, the proton–proton system has five complex amplitudes. If we eliminate one overall phase factor, specification of these amplitudes at one energy and angle requires nine numbers and hence nine independent experiments. If, however, measurements are made over all angles from 0 deg to 90 deg at one energy, then unitarity relations[12] relating real and imaginary parts of the amplitudes can be formulated. The result is that, in principle at least, five kinds of experiments at one energy and *all angles* suffice to specify the proton–proton scattering matrix at that energy.

Because all experiments contain statistical and other uncertainties, overspecification of the scattering matrix is desirable. If we do proton–proton measurements at energies above the pion-production threshold (280 Mev), then the unitarity relations are lost; so nine experiments are again required to specify the elastic-scattering matrix. In practice, inelastic effects are small up to 450 MeV, and accurate phase-shift analyses can be made up to that energy.

The neutron–proton system has five complex amplitudes for each of two isotopic-spin amplitudes. Because neutron–proton measurements from 0 deg to 90 deg and from 90 deg to 180 deg can be considered as independent experiments, five measurements over the angular range from 0 deg to 180 deg are enough to specify the neutron–proton scattering matrix for energies below 280 MeV. Unfortunately, neutron–proton data are often of limited statistical accuracy and often include only a few scattering angles. Also, neutron–proton experiments sometimes involve deuterium as a neutron target. This use makes a substantial and somewhat controversial correction necessary to remove the effect of the spectator proton that is contained in the deuteron.

Thus, except at lowest energies, attempts to analyze neutron–proton data by themselves[13] have been unsuccessful. If, however, proton–proton and neutron–proton data at the same energy are available, then the proton–proton data can be analyzed to give the $I = 1$ amplitudes, charge independence can be invoked to apply these to the neutron–proton scattering and the neutron–proton data can then be analyzed to give the corresponding $I = 0$ amplitudes. An analysis of this type was first published in 1961.

Neutron–neutron experiments are difficult; so few of them have been done. The main effort here has centered on the final-state neutron–neutron interaction that is produced when deuterium is bombarded with neutrons or pions. Results indicate agreement to within 1% with the concept of charge symmetry and to within a few percentage points with the concept of charge independence.[15]



POSSIBLE NUCLEON–NUCLEON EXPERIMENTS. Laboratory-frame diagrams show polarization component to be measured; a dot indicates a vector out of the page, and M indicates 90 deg precession in a magnetic field. —FIG. 3

Nucleon–nucleon experiments

As we have seen, in the most general case nine proton–proton experiments are needed to specify the elastic-scattering matrix at one energy and angle. Not surprisingly, it turns out that nine independent spin-space experiments can be simultaneously defined.[12,16] Experiments were first done by scattering protons once (σ), twice (P, C_{NN}, C_{KP}), and three times (D, D_T, R, R′, A, A′). Figure 3 describes these observables. The recent development, however, of polarized proton beams and polarized targets has enabled experimenters to reduce the number of scatterings by one and to improve greatly the accuracy and comprehensiveness of the experiments. This "second generation" of experiments is just now starting to have an important impact on nucleon–nucleon work.

Fairly complete sets of nucleon–nucleon data exist at 25, 50, 95, 142, 210, 330, 425 and 650 MeV. These energies correspond, naturally enough, to energies of existing cyclotrons. It is interesting that, their primary mission of measuring nucleon–nucleon scattering fulfilled, some of these cyclotrons are now being scrapped.

Phase shift analyses

One major difficulty in analyzing nucleon–nucleon data is that we have so little theoretical guidance. Scattering amplitudes are essentially unknown functions of energy E and scattering angle θ. The conventional way of dealing with this situation is to expand the scattering amplitudes in terms of angular-momentum states

$$a(E,\theta) = f(E)\, g(\theta)$$

The $g(\theta)$ are known functions that depend on the spin, orbital angular momentum and total angular momentum (S, l, J) of the system. The $f(E)$ are unknown functions of energy and are expressed in the following unitary form

$$f(E) \propto e^{i\delta(E)}$$

where the phase shifts $\delta(E)$ must of course carry labels S, l, J.

The spectroscopic form for the phase shifts[17]

$$\delta(E) \equiv {}^{2S+1}l_J(E)$$

is probably the prevalent notation today; notation used by the Yale group is very similar.[18] For the nuclear-bar phase shifts,[17] as used for example in our work at Livermore, the lowest states of the proton–proton system are: $^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$, ϵ_2, $^3F_2$, . . ., where S, P, D, F, . . . correspond to $l = 0, 1, 2, 3, \ldots$, and where ϵ_J is the mixing parameter.

The phase-shift decomposition of scattering amplitudes has several advantages: because a few low-l phases dominate the scattering the number of free (phenomenological) phases can be kept reasonably small; physical information can be inserted by using effective-range low-energy limits for S-waves; theory can be inserted by calculating the small, high-l phases from the one-pion-exchange Feynman diagram and the observed energy dependence of the phase shifts can be used to test theoretical models. The outstanding disadvantage of phase-shift formalism is that the equations are nonlinear.

Calculation of phases directly from experiment or of potentials directly from phases has proved to be impossible. It is necessary instead to go in the other direction. This means that we can determine a set of phase shifts only by making least-squares fits to the data, and we can determine parameters of a nuclear-force model only by making least-squares fits to the phases or to the data directly.

Phase-shift analyses can be made at a single energy (actually a narrow energy band), or over a whole range of energies. For a range of energies we must choose a set of parameters that express the energy dependence of the phase shifts, and these parameters are then varied to minimize the least-squares-sum χ^2. The only two groups to carry out large-scale energy-dependent analyses have been Breit's Yale group and the Livermore group. Energy-independent analyses have been carried out at several laboratories.

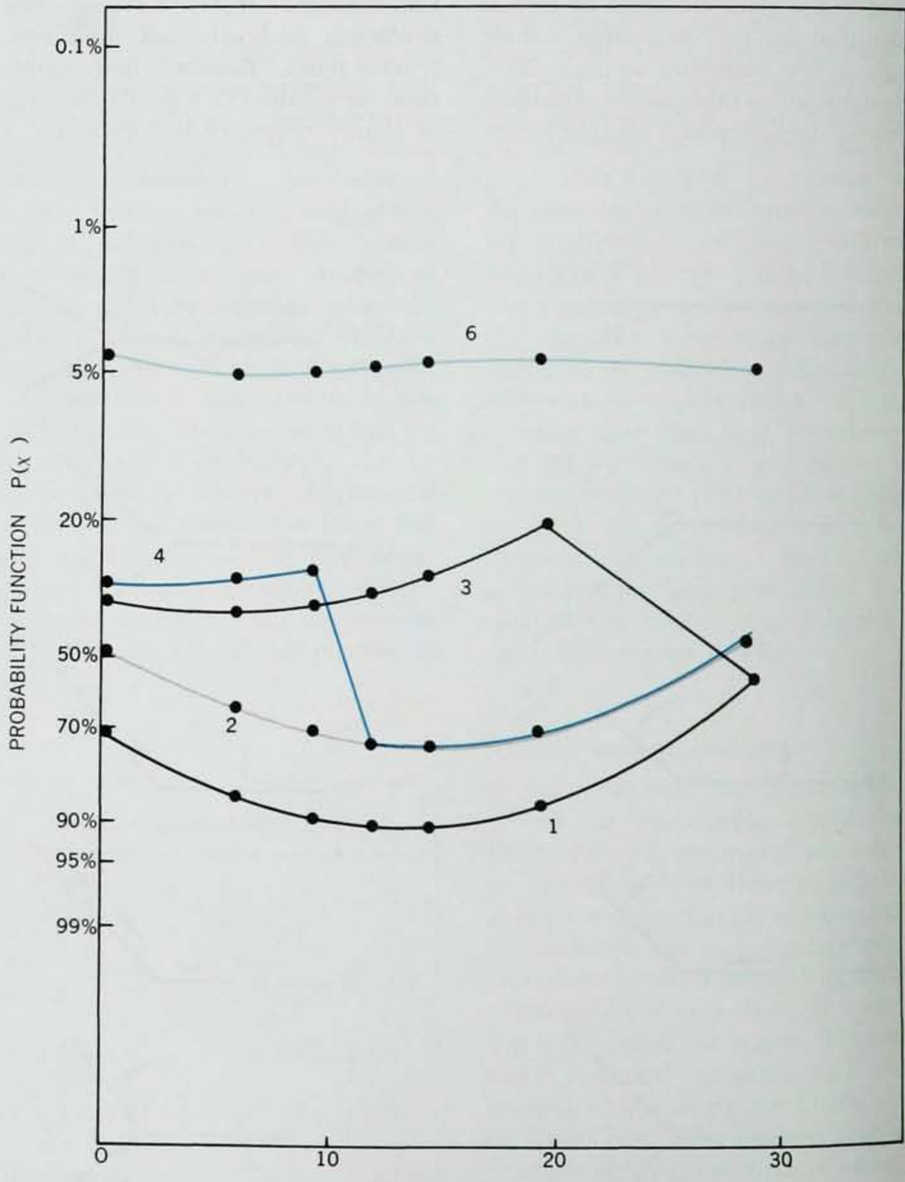
To determine phase shifts one selects a set of phases, calculates the corresponding observables, determines the least-square sum χ^2 for a fit to the data and then varies the phases to minimize χ^2. If the data are complete, statistically accurate and self-consistent, a unique solution (set of phases) results. In a typical analysis, 1000 to 2000 data may be included in the χ^2 sum. The variable parameters, which include both phase-shift coefficients and data-normalization constants, can number 100 or more. Thus selection of a method to minimize the parameters is a nontrivial part of the problem.

Early computer problems at Livermore used the grid-search method, in which one parameter at a time is varied. Because the parameters are highly correlated, this is a very inefficient method for a large problem. An improved method, used in early work at Yale,[18] is the gradient search in which all parameters are varied together but in an uncorrelated manner. The most efficient method for large problems is the matrix search,[19] in which all parameters are varied simultaneously along a correlated path in parameter space.

Although the matrix search has been used in other applications for a long time, its first application to the nucleon–nucleon problem was by Peter Signell.[20] The matrix search has an additional advantage; the error matrix for the solution is automatically obtained. At Livermore, a method of matrix reduction devised by Richard Arndt[19] is used to split phase parameters and normalization constants into a two-step minimization process. This method lowers the dimensionality of the matrices by almost a factor of 2 and greatly reduces computer storage requirements.

Early phase-shift results

The first use of a "computer" to attack the nucleon–nucleon problem was in the work done by E. Clementel and Claudio Villi[21] in 1955. Their computer was a set of mechanical arms that could be set to give an analog simulation of certain scattering-amplitude functions. They were able to show that, given only proton–proton



PROBABILITY FUNCTIONS for 310-MeV Stapp phase-shift solutions. The maximum probability obtained for Stapp solutions 1 and 2 at $g^2 = 14$ agrees with the $g^2 = 15$ value obtained from pion-nucleon scattering analyses. —FIG. 4

differential cross-section data, there are four sets of P-phases for each value of the S-phase (up to some maximal value for S), and all give precisely the same fit to the data. This work was later adapted at Livermore[22] for UNIVAC I, the world's first true electronic computer.

Modern phase-shift analysis started at Berkeley. In 1956 a group using the 184-inch cyclotron completed measurements of σ, P, D, R and A at 315 MeV.[23] Armed with these data, Henry Stapp and his collaborators, who had access to Livermore and Los Alamos computers, did a proton–proton phase-shift analysis. They used 14 free phases (S-H waves), set the remainder equal to zero and found five acceptable phase-shift solutions.

Following the lead of the Japanese school,[24] Michael Moravcsik[25] and A. F. Grashin[26] independently proposed that the Stapp analysis could be improved by calculating the higher phase shifts from one-pion exchange (OPE) instead of just setting them equal to zero. This reduced the number of acceptable solutions to two, called "Stapp solutions 1 and 2." In addition, the pion–nucleon coupling constant, which enters into the calculation of the OPE phases, was shown for the first time to have a nucleon–nucleon analysis value consistent with that obtained from pion–nucleon analyses. These results are illustrated in Figure 4. Subsequent analyses of Rochester proton–proton data at 210 MeV[27] showed that the Stapp-solution types 1 and 2 occurred there also. Later analyses have shown that Stapp solution number 1 is the correct one.

The first energy-dependent analysis of proton–proton scattering was carried out by the Yale group,[28] and was soon followed by a similar analysis at Livermore.[29] Subsequent Yale analyses[14] included both proton–proton and neutron–proton scattering.

Recent elastic-scattering studies

Analyses of energy-independent phase-shifts have been carried out by groups at Berkeley, CERN, Dubna, Harwell, Kyoto, Livermore, and Michigan State. All used essentially the same method of analysis; differences in solutions can be attributed to slightly different choices of data or of the number of phenomenological phases. The results of these analyses are in general agreement with each other.

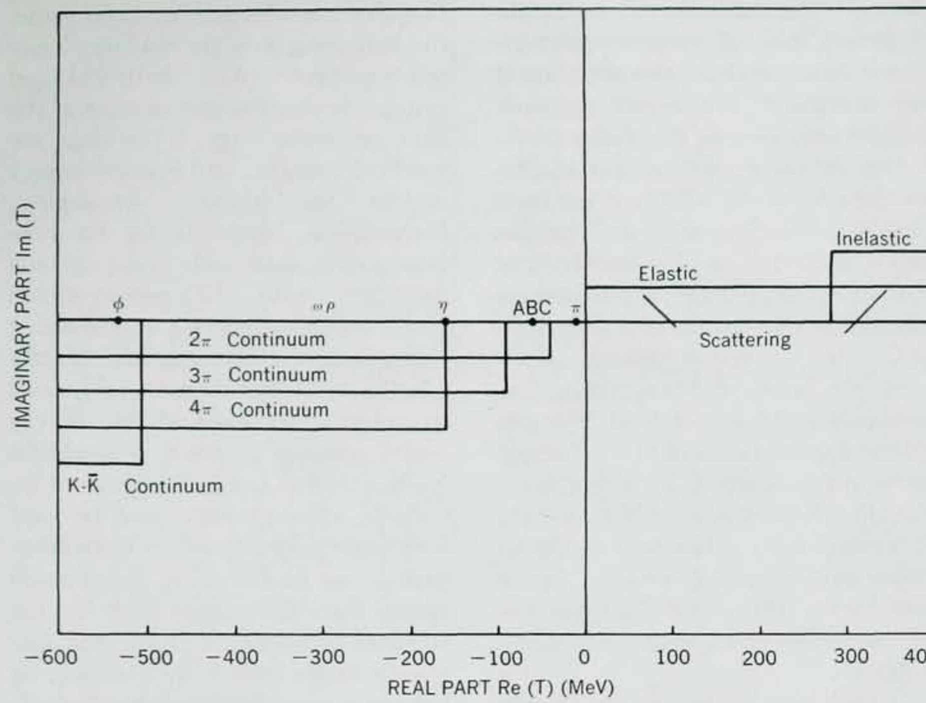
The Yale group[11] has carried out energy-dependent phase-shift analyses of proton–proton and neutron–proton scattering from about 10 MeV to 350 MeV. We at Livermore have completed similar analyses from about 1 MeV to 450 MeV[30] and additional analyses extending to 750 MeV.[31,32] The Yale group, in choosing energy-dependent forms for the phase shifts, selected pure mathematical functions with the requisite flexibility to fit their data.

At Livermore functions that have a singularity structure[19] and threshold behavior[33] consistent with the dictates of the Mandelstam representation were used (see figure 5). In regions where data are complete and accurate enough to set limits on the solution, the Yale and Livermore phase-shift values are in reasonable agreement. This agreement indicates that neither analysis is appreciably form-limited and that energy dependences obtained for phase shifts are reliable. As further confirmation the Livermore work also includes single-energy analyses at 25, 50, 95, 142, 210, 330, and 425 MeV. The energy-dependent and energy-independent phase shifts are in agreement; this agreement would not occur if the energy-dependent forms were too rigid.

These phase-shift results fulfill the longstanding goal of obtaining a set of nucleon–nucleon scattering amplitudes that cover continuously the entire elastic-scattering region. The final Livermore analysis includes 1076 proton–proton data from 1 to 450 MeV and 990 neutron–proton data from 0.5 to 425 MeV. 52 phenomenological parameters representing 27 elastic phases and one inelastic phase are sufficient to give a statistically accurate fit ($\chi^2 = 1.1$ per data point) to the entire collection of 2066 data spanning this energy range. Also, because the parametrization is continuous and mathematically well defined, the parameter error matrix gives statistically determined uncertainties in the phases and in all functions of the phases over the energy range.

Remaining problems

There are still some difficulties with phase-shift analyses, particularly with the $I = 0$ amplitudes. At low energies we expect from the sign of the deuteron quadrupole moment that the ϵ_1 coupling parameter should be positive.[34] Also, the $^1P_1$ phase shift might be expected to approximate its OPE value at low energies. Phase shift analyses, however, often give anomalous values below 50 MeV for these



SINGULARITY STRUCTURE in the complex kinetic-energy plane for nucleon–nucleon scattering amplitudes. Poles on negative real axis become cuts when a partial wave projection is made. Left-hand singularities correspond to nuclear forces, and right-hand singularities are unitarity cuts. Here $T = 4K^2/2M$. —FIG. 5

phases. The difficulty can be attributed to a lack of accurate neutron–proton differential cross-section data at low energies,[30] but recent measurements[35] may remedy this deficiency.

Unfortunately, existing neutron–proton data below 50 MeV are not completely self-consistent. At energies above 210 MeV, and particularly at 330 MeV, the neutron–proton data are incomplete enough that an accurate $I = 0$ matrix can not be defined. However, the latest triple-scattering neutron–proton data at 425 MeV[36] give a well defined result for $I = 0$ amplitudes at that energy. By adding these data to the energy-dependent analysis, it is possible to obtain reasonably reliable neutron–proton phase shifts at 330 MeV. This result illustrates one of the virtues of an energy-dependent analysis.

To achieve accurate fits to the data below 10 MeV, one must apply vacuum-polarization corrections to the proton–proton amplitudes and use separate $^1S_0$ phases for the proton–proton and neutron–proton systems. The data are now so accurate that failure of charge independence for the $^1S_0$ phase must be taken into account.[11] The other phases do not yet require this additional freedom.[30]

At energies above 280 MeV inelastic effects should be considered. Up to 450 MeV, inelastic scattering is less than 10% of elastic scattering. On theoretical grounds it is reasonable to attribute this small inelasticity entirely to the $^1D_2$ phase shift. Inclusion of an inelastic component in the $^1D_2$ phase does not appreciably lower χ^2, but it gives slightly different and more realistic phase-shift values.

To summarize the proton–proton situation, 1076 carefully selected proton–proton data form a set that spans the 1–450 MeV region. This set yields good statistical accuracy, reasonable completeness at selected energies and self-consistency within the data set. These data determine a unique phase-shift solution; scattering amplitudes are accurate to within a few percent over the entire elastic energy range and up to about 450 MeV. Restrictions imposed by fitting all of these data simultaneously are stringent enough that inconsistencies between these data and any new measurements can be promptly identified.[37]

The neutron–proton situation is not so favorable: the 990 experimental points form a set that spans the energy region from 0.5 to 450 MeV, but although some selection has been made, the remaining data are not completely self-consistent. Also, statistical and systematic uncertainties in some of the data are quite large. The data are nowhere complete and in many energy regions are woefully incomplete. Nevertheless, by combining the neutron–proton data with proton–proton data (or with the proton–proton $I = 1$ scattering matrix) and invoking charge independence, we can obtain a solution type that is reasonably well delineated over most of this energy region. Errors in the $I = 0$ phases given by error matrices appear to be realistic, although they must be used with some reservations; an incomplete data set can lead to actual errors much larger than those predicted by the standard statistical analysis, and systematic errors caused, for example, by improper corrections for binding effects in the deuteron, would not be reflected in the error-matrix calculations.

Errors in energy-dependent phases are given by the parameter error matrix. These should be regarded as the smallest possible errors and would be the true errors if the energy-dependent forms were correct. Errors given by energy-independent analyses should be regarded as the greatest possible errors and would be the true errors if experiments at one energy were completely uncorrelated with experiments at other energies. By carrying out both types of analysis, we can obtain bounds for the errors. Because phase shifts are highly correlated, so are the errors. To obtain accurate statistical results in fitting to a model, one must use the full error matrix; the diagonal components are not sufficient.

Recent inelastic-scattering work

Inelastic corrections are small and can be appropriately handled at energies up to 450 MeV. Few data exist in the region between 450 and 600 MeV, but from 600 to 700 MeV quite a complete proton–proton data set exists. Most of the data are from Dubna,[38] but substantial contributions have been made at other laboratories, such as Berkeley and Saclay, France. The big difficulty at 650 MeV is that the inelasticity is now roughly 40% of the total scattering, and simple treatment of inelastic phases does not suffice.

Phase shift studies have been made at 650 MeV,[39] and solutions can be obtained that give excellent fits to the data. These solutions, however, involve a somewhat arbitrary handling of the inelasticity; one must apportion the inelasticity among a number of phase shifts, and there is remarkably little theoretical guidance as to just how to do this. In studies at Livermore[31] we tried many different models for the inelasticity, and we obtained a corresponding number of elastic phase-shift solutions. Coupling between inelastic and elastic processes is strong.

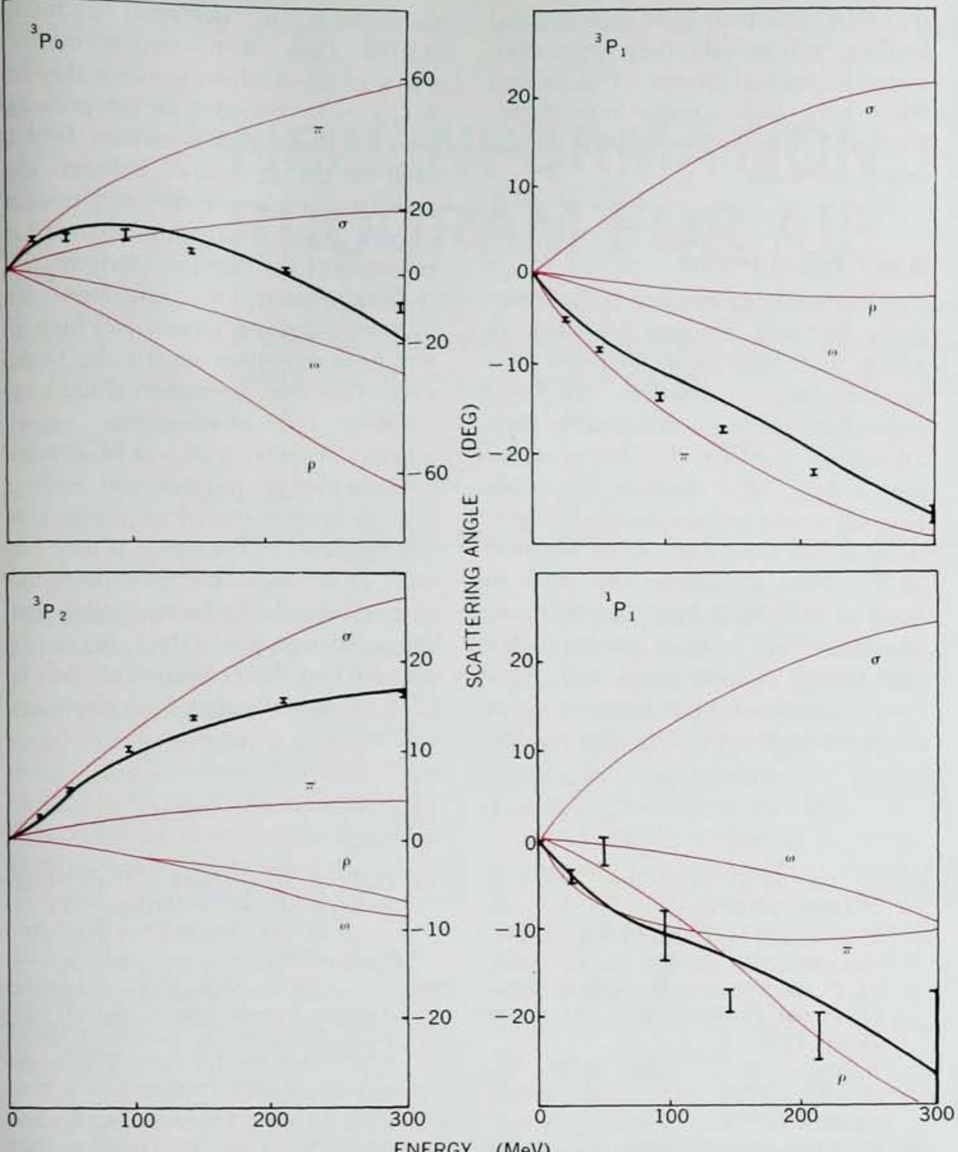
Our conclusion at Livermore (to which some of our colleagues do not wholly subscribe[40]) is that a definitive set of proton–proton phases at 650 MeV can not be obtained from present data and the present state of inelastic-scattering theory. Nine complete proton–proton experiments would in principle define the proton–proton elastic-scattering matrix at 650 MeV, but these experiments do not yet all exist. The data on inelastic scattering and the theory to handle these data are both very sketchy. High-intensity cyclotrons planned for the Swiss Federal Institute of Technology, Zürich and for Los Alamos should supply important new measurements in this energy region.

Any 650-MeV neutron–proton analysis, because it necessarily depends on $I = 1$ amplitudes obtained from proton–proton scattering and on $I = 0$ inelastic effects, is thus almost meaningless. Solutions can be obtained that give precision fits to the data, and the magnitudes of the large $I = 0$ phases can be roughly determined. But small uncertainties in $I = 1$ amplitudes become large uncertainties in addition to uncertainties for the $I = 0$ amplitudes.

As far as definitive phase-shift analyses of the nucleon–nucleon system are concerned, I feel that present experimental and theoretical situations combine to impose a sharp cutoff at 450 MeV; this is perhaps just a way of saying that the opportunities exist at higher energies.

Implications for theory

The outstanding theoretical success in the nucleon–nucleon field in the last decade has been the one-boson-exchange (OBE) model.[41] The only part of the nuclear force that can be calculated unambiguously from field theory is that due to exchange of a single (virtual) particle, the pion. If, however, we consider narrow resonances in multipion states as "particles," then we can calculate their contributions to the nuclear force. It is a remarkable fact that if the pion, the



P-WAVES as determined experimentally (error flags) and as calculated from one-boson exchange. π, ρ, ω and σ Born terms all make important contributions, and the sum (heavy solid line) is in good qualitative agreement with experiment. —FIG. 6

ρ and ω resonances and a strong scalar–isoscalar interaction (taken for convenience to be the σ resonance) are treated in Born approximation, they give phase-shift values for P-waves and higher that are in good qualitative agreement with experiment for proton–proton and neutron–proton scattering over the elastic-scattering range (see figure 6). Furthermore, masses and coupling constants that must be used to obtain this good fit agree with values that can be deduced from direct measurements and other physical processes.[42]

There are, however, definite limitations to the one-boson-exchange model; unitarity corrections to the Born terms are small and unimportant for the high-l amplitudes and are large and unbelievable for the lowest-l amplitudes. Thus, although the lowest-order OBE model is a good one, it is difficult to improve. The challenge imposed on theorists by the OBE model is to explain the existence of the ρ and ω resonances. Just why these saturate their 2π and 3π quantum states, and why they contribute so decisively to the nuclear force, is in my opinion the main question to be answered by nucleon–nucleon theorists. From nucleon–nucleon analyses, we can not conclude much of anything about the width of the σ resonance. A strong enhancement in this state, however, is certainly required to fit the data.

The challenge at higher energies is to calculate, in a useful way, the pion-production amplitudes. It is clear from low-energy work that exchange of a single virtual pion is the dominant mechanism in all phases (even including P-waves!) except S-waves. At energies above 280 MeV we are in the regime where a real pion is produced. One feels intuitively that ability to handle the appearance of a real pion from the virtual cloud surrounding a nucleon would contribute substantially to understanding the properties of that cloud.

Another challenge, one that may perhaps be studied at both lower and higher energies, is to see what limits nucleon–nucleon scattering data impose on interaction at very short distances.[43] The hard core has recently become in many models a softer core, and the nature of the core region is important in nuclear-structure calculations. The extent to which measured nucleon–nucleon amplitudes limit this region, and the relevance of these amplitudes to phenomena like the nonlocality of the potential, remain fruitful areas for investigation.

At the crossroads

In the 1930's broad features of nucleon–nucleon interaction were determined. The ensuing three decades have seen this work extended experimentally until now a reasonably complete mapping has been obtained for proton–proton and neutron–proton scattering over the entire elastic energy region. Roughly speaking, this mapping has an accuracy of perhaps 5% for proton–proton scattering and 10% for neutron–proton scattering. This accuracy is good enough to impose reasonable bounds on potential models, and to make it appear unlikely that any major surprises will occur if these experiments are extended at the same level of sophistication.

The experimenter's choice is to retire or to aim for the 1% level. At Harvard and Rochester the choice was to retire. At Berkeley, Chicago, Dubna, Los Alamos and Orsay, experiments featuring polarized targets are superseding older triple-scattering experiments. At Saclay, a recent entrant into low-energy nucleon–nucleon work, a high intensity polarized proton ion source has been developed. Similar beams for low-energy measurements have been developed at Berkeley and Los Alamos.

At 1%-accuracy level, phase-shift analyses must include careful corrections for magnetic-moment effects, vacuum-polarization effects and manifestations of charge-independence breakdown. Theoretical models should begin to show some sorting of 2π and 3π effects. Because experimental uncertainties are magnified in analytically continuing the scattering amplitudes off the energy shell, improved accuracy would permit a better determination of the usefulness of the bootstrap concept in this area.

In the inelastic region, the right turn at the crossroads would lead to a double-barreled experimental-theoretical attack on the nucleon-nucleon problem. Theorists must derive models for production processes, tell experimentalists just what kind of pion-production experiments they need to test the models, recheck their models with the experiments and repeat the process. An on-line collaboration is needed to get meaningful results in this difficult area. The planning groups at Zürich and Los Alamos see the need for this kind of close collaboration between theory and experiment, and their new experimental facilities will include, they hope, associated theoretical groups. Dubna, and other very high energy laboratories have of course followed such as approach for years.

A new field of physics

One outcome of this work is the emergence just now of a new field that we might call intermediate-energy elementary-particle physics. High-energy physicists have remarkably little interest in anything that happens below a few GeV; nuclear physicists have no reason to be interested in anything higher than a couple of hundred MeV. Thus physicists who wish to work at 500 MeV find that they are no longer welcome at the crowded high-energy conferences, and they can't understand what is going on at the nuclear-physics conferences. So they have, in desperation, finally started their own conferences.[39,44] For nucleon-nucleon workers, this difficulty with energies is compounded because the nucleon-nucleon field is itself in the gray area between elementary-particle physics and nuclear physics. Does it belong in volume 4 or volume 5 of the Physical Review?

Development of polarized ion sources, polarized targets and high-intensity accelerators signals the beginning of the next generation of nucleon-nucleon and pion-nucleon experiments. Workers in this field of intermediate-energy physics will form a more distinctive branch of physics than was apparent in the past. If they succeed, however, in knocking down any of the formidable barriers that limit our present understanding, we can be assured that the consequences will be felt by their colleagues both above and below.

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