DOE/ER/05223-35

MASTER

MEDIUM-ENERGY THEORY GROUP

PROGRESS REPORT

for

DOE Contract No. DE-AS05-76ER05223

March 1, 1980 - February 28, 1981

entitled

"Intermediate-Energy Nuclear Theory"

submitted by the

TEXAS A&M RESEARCH FOUNDATION

to the

U. S. DEPARTMENT OF ENERGY

Prepared by

Dr. R. A. Bryan

Dr. B. J. VerWest

and

Dr. C. A. Dominguez

Physics Department, Texas A&M University

College Station, Texas 77843

December 1980

Abstract

We report on work carried out during the contract period by co-principal investigators R. A. Bryan, B. J. VerWest, and C. A. Dominguez, faculty associates R. B. Clark and H. Garcilazo, and postdoctoral associate D. Eyre. We have placed primary emphasis on investigating the nucleon-nucleon interaction at medium energies, and have initiated a major program in collaboration with members of the Center for Analysis of Particle Scattering at VPI&SU, to extract the experimental scattering amplitudes from the NN data over the 0 to 850 MeV energy range. We have set up special sub-programs to handle the large amount of data involved, and to estimate the total reaction cross sections. We have also completed a program to project out partial-wave amplitudes of a tree-graph model for $NN \rightarrow NN\pi$, in order to supplement the data in the higher angular momentum states.

Work has also been carried out on the three-body problem, particularly π-deuteron scattering, and on setting up an appropriate formalism for the two-to-three particle process $NN \rightarrow NN\pi$. In strong-interaction related work, the pion-nucleon sigma term has been investigated, and the dual-model prediction for factorizable three-hadron form factors confirmed. Finally, we have continued a study of isospin as a dynamical operator in an extended space.

Table of Contents

I. Introduction

We have carried out research on a variety of topics but with principal emphasis on nucleon-nucleon scattering at intermediate energies. Of primary importance is the determination of the experimental NN S-matrix, and in collaboration with R. A. Arndt and L. D. Roper of the Center for Analysis of Particle Scattering at VPI&SU, we have found single-energy solutions at fourteen energies between T_{lab} = 25 MeV and 800 MeV. We have also determined smooth energy-dependent solutions between 0 and 850 MeV. (This is detailed in sec. A1.) Extracting the NN phase shifts over such a broad energy range means handling huge amounts of data, and we have had to set up a special program just to find, evaluate, and store these data (see sec. A2). To carry out analyses where $NN \rightarrow NN\pi$ competes strongly ($T_{lab} \gtrsim$ 400 MeV), we have also had to synthesize total reaction cross section data where none exist, by integrating over the charge-channel pion-production data assuming isospin invariance. This has worked fairly well, and has also served as a constraint on the inelastic data (see A4). Nevertheless, much new data are needed, particularly np triple-scattering measurements at the higher energies. To supplement the data we have carried out partial-wave projections of a successful $NN \rightarrow NN\pi$ "tree-diagram" model and used these contributions for $\ell \geq 4$ (see A5). The most spectacular feature of the resultant S-matrix has been the resonance-like features in the $^1D_2$ and $^3F_3$ states around 500 and 700 MeV, respectively. Controversy continues as to whether or not these are true reasonances, and if they are true resonances, whether they involve color-quark clusters or just colorless hadronic clusters. One opinion on the first question is given in sec. A6.

Parallel to our effort to determine the NN amplitudes experimentally has been our effort to calculate them theoretically. Above the threshold for pion production this becomes a formidable problem. As a first step we have cast the two-to-three particle Avishai-Mizutani dynamical equations in a K-matrix formalism, and satisfied the unitarity constraints with Heitler-type integral equations (see sec. B1). We have also studied various aspects of the three-hadron scattering problem. The cluster-expansion method of Eyre and Osborn for solving the three-body problem has been tested for some simple cases (sec. B2). We have also carried out realistic calculations of pion-deuteron scattering using relativistic Faddeev equations (secs. B4 and B7), and studied relativistic effects in the three-body bound-state problem (sec B6). We have also developed energy-dependent separable two-nucleon potentials in an effort to streamline three-body calculations (secs. B3 and B5).

We have also addressed diverse problems in strong-interaction dynamics such as the pion-nucleon sigma term (see sec. C1) and three-point vertex functions. With regard to the latter, we see evidence supporting the important dual-model prediction that the vertex function factorizes (see sec. C2). Finally we have continued investigating the conjecture that isospin is not a discrete symmetry but rather a dynamical effect in an extended space (sec. C3).

The co-principal investigators, R. A. Bryan, Professor, B. J. VerWest, Assistant Professor, and C. A. Dominguez, Visiting Associate Professor, have each spent about 50% of their time during the ninemonth academic year on research related to this contract. Faculty associates R. B. Clark, Associate Professor, and H. Garcilazo, Visiting Assistant Professor, have spent a like amount of time. All the above personnel have devoted full time to the contract during the three summer months. D. Eyre, postdoctoral associate, and J. Gruben, graduate student, have worked full time during the contract year.

II. Specific Research Topics

A. Nucleon-Nucleon Theory and Phase-Shift Analysis

1. Phase-Shift Analysis of Nucleon-Nucleon Scattering Data (B. J. VerWest, R. A. Arndt, L. D. Roper, R. B. Clark, and R. A. Bryan)

We have completed preliminary energy-dependent and single-energy NN scattering amplitude analyses which reflect improvements in our analysis procedures and the inclusion of new experimental results. We have tabulated the amplitudes from these analyses in a recent report[1] which represents the status of this work as of August 1980. This is an ongoing effort, as refinements continue to be made and more data arrive. Work is also continuing on the existing solutions to check their accuracy, determine where new measurements are needed, and produce a "standard" set of amplitudes.

There have been several changes in the analysis procedure relating to the amplitudes above the pion-production threshold. First it was discovered that to preserve the optical theorem, the one-pion-exchange contribution which was used for high partial waves must be unitarized up to $\ell \gtrsim 10 - 15$. The normal procedure of adding the non-unitary Born term above $\ell \sim 6$ lead to violations of the optical theorem of about 3% at 650 MeV and the wrong shape for the np differential cross section near 180° where recent LAMPF data are very precise. It has also been pointed out that the earlier parameterization sometimes resulted in amplitudes that violated conservation of probability (general two-body unitarity).[2] Thus we have adopted a new parameterization for the S-matrix which is closely related to the complex extension of the nuclear bar phases, reduces to the nuclear bar phases below production threshold and is constrained from ever violating conservation of probability.

In an effort to obtain reaction cross section data needed to constrain the inelasticities, we have made an energy-dependent isospin analysis of pp and np charge-channel reaction cross section data below 1200 MeV (see sec. 4). While there are almost no total reaction cross section data, there is adequate information in the charge-channel data and this has been used to generate pseudo-data for pp and np total reaction cross section for the analyses until better information becomes available. We are also working to improve the bases for expansion of the inelastic part of the scattering amplitudes in the energy-dependent program so that they may more readily follow the trends now emerging from the single-energy analyses. We have also included as pseudo-data, the dispersion-theoretical parameters of Grein and Kroll which are the ratio of real to imaginary forward amplitudes.

The data base for these analyses continues to grow and, in collaboration with P. Signell we are attempting to completely screen and refine it (see following section). A considerable amount of new data has been included above the production threshold which has stabilized the higher energy solutions. Most notable are the recent np Ay and Ayy measurements in the range 395-665 MeV (ref. 3) and pp A, R and D at 800 MeV (ref. 4). The energy-dependent analysis is used to initially encode the data as a starting point for the single-energy analyses. The single-energy analyses are used to obtain error matrices and best reflect the uncertainty in the amplitudes at any given energy. The single-energy analyses up to 425 MeV are very stable and have few problems. The set of overlapping analyses from 500 to 800 MeV has been used to study the trends of the phases above production threshold, and with the latest LAMPF np data, the solutions up to 650 MeV are becoming well defined. The only energies where the solutions are not well defined are 700 and 750 MeV for I = 0, where there are still no np data except differential cross sections and polarizations, but even these solutions line up well with other solutions.

These phase shift analyses show a high degree of consistency between the energy-dependent form and the single-energy analyses, and encode the existing data quite accurately in general. Some isolated problems still exist at lower energies and there is still a great need for more data, especially np spin correlation experiments around 800 MeV. The high χ^2 for the 750 and 800 MeV solutions comes mainly from some pp differential cross section and polarization data at 800 MeV; these data have extremely small errors which may be unrealistic.

"Current" solutions and all predictions and data pertaining thereto are available through an interactive dial-in computer program at VPI&SU. Information on the use of this system can be obtained from either TAMU or VPI upon request. This system will eventually contain the more stable "standard" solutions which will encode data and be updated every six months to a year.

1. R. A. Arndt and B. J. VerWest, DOE/ER/05223-29.

2. R. A. Bryan, DOE/ER/05223-21 (revised).

3. T. Bhatia, contributed paper to Polarization Symposium, Santa Fe, 1980.

4. M. McNaughton, contributed paper to Polarization Symposium, Santa Fe, 1980.

2. Nucleon-Nucleon Data Collection

(R. B. Clark and B. J. VerWest)

We have made an extensive effort to document, confirm and complete the data base for the nucleon-nucleon interaction at energies up to 1000 MeV. We have taken as our starting point the data base which was established at Livermore[1] and has been extended and maintained by Arndt and Roper[2] for many years. The original publications which document these numerous data sets have been assembled, surveyed and compared point by point with the data base. Corrections have been made in the few cases where entry errors have been found. Appropriate modifications have been made where data sets represent duplication or where independent data sets were inadvertently combined. Detailed comparisons have also been made with the recently updated nucleon-nucleon data compilation of Bystricky and Lehar.[3] The format of the data base has also been changed in order to provide easier identification of the nature and source of each data set.

We have carried out a detailed search of the literature to identify nucleon-nucleon data sets which may have been missed. In an effort to maintain the completeness of the data base, we have made a significant effort to identify and add all new data sets as they become available. We find that most experimental groups continue to submit their new data to our collaboration as they become available. Regular personal communications with most of the experimental groups active in nucleon-nucleon work have also helped us to keep up with new data.

In addition we have implemented a systematic process for utilizing the computer-based current-literature search documentation service at DESY to identify newly published data. Weekly searches of Preprints in Particles and Fields and Preprints in Nuclear Physics have been made to locate new nucleon-nucleon data as soon as possible.

1. M. H. MacGregor, R. A. Arndt, and R. M. Wright, UCRL-50426, Livermore (1968).

2. R. A. Arndt, R. H. Hackman and L. D. Roper, Nucleon-Nucleon Scattering Analyses, II. Report of VPI&SU (1976).

3. J. Bystricky and F. Lehar, Nucleon-Nucleon Scattering Data (Fachinformationszentrum Energie-Physik-Mathematik, Karlsruhe, 1978).

3. Parameterization of Inelastic NN Scattering in Coupled Angular-Momentum States

(R. A. Bryan)

We have parameterized the inelastic coupled-channel S-matrix for nucleon-nucleon scattering[1] as

(1) $$S_{4\times 4} = \mathcal{U}\,\mathcal{U}^T$$

(T denotes transpose), where U is a unitary 4x4 matrix of the form

$$\mathcal{U} = \prod_{j=1}^{9} \exp i\theta_j \gamma_j$$

and where the θ_j are (linear combinations of) nine real phase parameters and the γ_j nine hermitean 4x4 matrices. The four channels come from coupling a pair of angular momentum states to a pair of reaction channels, say NN and N-Roper. In the NN-NN scattering sector, eq. 1 reduces to

(2) $$S = e^{i\delta} e^{i\varepsilon} N e^{i\varepsilon} e^{i\delta},$$

where

$$\delta = \begin{pmatrix} \delta_\alpha & 0 \\ 0 & \delta_\beta \end{pmatrix}$$

$$\varepsilon = \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & 0 \end{pmatrix}$$

and where N is as real symmetric 2x2 matrix embodying all the inelastic information. For purely elastic scattering, $N = 1_{2x2}$ and S reduces to the Stapp-Ypsilantis-Metropolis form (SYM "bar" parameterization).

We have discovered that this format (eq. 2, r.h.s.) parameterizes

S with small phases θ_i when the interaction is weak, and that this format also automatically satisfies a unitarity condition we have found, namely,

$$\det(1 - SS^{+}) \geq 0. \quad (3)$$

Neither of the two parameterizations quoted in the literature[2,3] have this property; the MacGregor-Arndt-Wright and Hoshizaki parameter ϕ can execute wide (360°) excursions for small changes in S, and care must be taken lest a given set of parameters violates eq. 3.

1. R. A. Bryan, DOE/ER/05223-21 (revised).
2. H. Hoshizaki, Suppl. Progr. Theoret. Phys. 42, 1 (1968).
3. M. H. MacGregor, R. A. Arndt, and R. M. Wright, Phys. Rev. 169, 1149 (1968).

4. Isospin Analysis of NN Reaction Cross Section Data

(B. J. VerWest and R. A. Arndt)

The NN reaction cross section for I = 0 and I = 1 scattering is an important piece of information needed as input for NN analyses and as a test for pion product theories. Unfortunately in the region $T_L \lesssim 1400$ MeV there are essentially no pp or np total reaction cross section data. Rather there is an assortment of reaction cross section data for the various charge channels. Data in this form cannot be used for inelastic NN analysis. However, by using isospin invariance and smooth interpolation one can extract the necessary isospin reaction cross sections $\sigma_{I_i I_f}$ (where I_i and I_f are the initial and final NN isospins). Preliminary analyses of this type have indicated a conflict in the existing data. Recent precise data on the reaction $np \rightarrow nn\pi^+$ [1] indicate that the problem lies in an overall systematic error in the old Dubna π° production experiments. Thus we have deleted the Dubna $np \rightarrow np\pi^\circ$ data from the analyses. The results indicate a very small I = 0 NN inelastic cross section with no evidence for resonance-like structure, and a large and relatively well-determined I = 1 NN inelastic cross section. These results are being used as constraints on our current NN phase-shift analyses.

1. M. Kleinschmidt et al., Universität Freiburg preprint (1980).

5. Peripheral Model for $NN \rightarrow NN\pi$

(J. H. Gruben and B. J. VerWest)

The success of earlier peripheral-model calculations of $NN \rightarrow NN\pi$[1] has lead to work on the partial-wave projection of these transition matrix elements. This will allow an approximate treatment of initial and final-state interactions as well as a better understanding of the partial-wave content of the production process.

The preliminary results of the partial-wave projections give partial-wave reaction cross sections and inelasticities in very good agreement with the analysis results and with other calculations based on NN and NΔ transition potentials[2] and πNN three-body calculations.[3] The important common feature of all these models is the Δ resonance, and its dominance of this reaction leads to the hope that the high partial waves are to a large extent model-independent. In the I = 1 channel where the Δ dominates the production reaction, the important feature is the relatively large inelasticity in the $^1D_2$, $^3F_3$, $^1G_4$ and

$^3H_5$ channels. This pattern follows from the coupling of the NN entrance channel to a NΔ channel of L = J-2 which is the lowest possible L state for a given J and thus minimizes the centrifugal barrier. Hence these states have enhanced reaction cross sections. The large cross sections in the $^1D_2$ and $^3F_3$ channels are reproduced without the inclusion of resonance-like structures and seem to be a result of the dynamics and angular-momentum coupling.

In the I = 0 channel where the Δ is excluded, the peripheral model indicates that the primary inelasticity is in the $^3S_1$ - $^3D_1$ and $^1P_1$ channels, with the $^3D_1$ being the most important. This is consistent with the analyses and indicates that higher partial-wave inelasticities need not be included at this time.

1. B. J. VerWest, Phys. Lett. 83B, 161 (1979).
2. A. M. Green and M. E. Sainio, Journal of Phys. G 5, 503 (1979).
3. W. M. Kloet, J. A. Tjon and R. R. Silbar, Rutgers University report RU-80-238 (1980).

6. On the Existence of Dibaryon Resonances in I = 1 $^1D_2$ and $^3F_3$ Nucleon-Nucleon Scattering

(R. Bhandari, R. A. Arndt, L. D. Roper and B. J. VerWest)

In order to study the details of the resonance-like structure seen in the $^1D_2$ and $^3F_3$ partial waves, we have made coupled-channel K-matrix fits to the NN amplitudes.[1] These fits include the NN and NΔ channels as well as the proper phase space and threshold dependence, and produce T-matrices which satisfy the basic constraints of analyticity and two-body-unitarity. These parameterizations fit the existing amplitudes from the VPI&SU - TAMU[2] analyses very well and reveal poles coupled strongly to the NΔ channel. The precise pole positions are uncertain and depend to some extent upon the particular parameterization scheme which is being employed. The proximity of the poles to the NΔ branch point suggests an interpretation of an S-wave (P-wave) NΔ "bound" or "virtual" state coupled to the $^1D_2$ ($^3F_3$) partial wave. These results are in contradiction to recent results of Kloet, Tjon and Silbar[3] and our own $NN \rightarrow NN\pi$ [4] calculations which indicate that the resonance-like behavior is a result of angular-momentum coupling and NΔ dynamics in lowest order and not a resonance which results from unitaritization of a singularity-free potential. This subject has been a topic of much debate lately and all these results must be studied more to understand this contradiction.

1. R. Bhandari, R. A. Arndt, L. D. Roper and B. J. VerWest, DOE/ER/05223-33.
2. R. A. Arndt and B. J. VerWest, DOE/ER/05223-29.
3. W. M. Kloet, J. A. Tjon and R. R. Silbar, Rutgers University report RU-80-238 (1980).
4. Work of J. Gruben and B. VerWest reported in the preceding section.

7. Time-Reversal Noninvariant NN Scattering

(R. A. Bryan, J. Binstock and A. Gersten)

Recently H. E. Conzett, R. J. Slobodrian and their collaborators[1] have measured an incredibly large difference between polarization (P) and asymmetry (A) in the reaction $^{7}Li\ (^{3}He, \vec{p})^{9}Be$ at helium ion energies of 14 MeV. These measurements, if confirmed, would imply a massive breakdown of time-reversal invariance in the strong interaction. In view of this, we have updated our manuscript on short-range time-reversal noninvariance in nucleon-nucleon scattering[2] and resubmitted it to Annals of Physics where it has been accepted for publication.

1. H. E. Conzett, P. vonRossen, F. Hinterberger, R. J. Slobodrian, C. Rioux, and R. Roy, Lawrence Berkeley Laboratory report LBL-11576 (1980).

2. J. Binstock, R. Bryan, and A. Gersten, ORO-5223-03 (second revision).

B. Three-Hadron Systems

1. Unitary Model for the πNN-NN Systems

(D. Eyre and B. J. VerWest)

We have constructed a unitary model for the coupled πNN-NN problem[1] by extending the Sasakawa-Karlsson K-matrix formalism[2] to the dynamical theory of Avishai-Mizutani.[3] The resulting system of Heitler-type on-shell integral equations serves to unitarize the scattering problem. The solution of these on-shell equations preserves both two- and three-body unitarity. The dynamical theory of Avishai-Mizutani is fully contained in equations for the K-matrix, which have zero discontinuity along the real positive-energy axis and are therefore amenable to approximation without affecting the unitarity constraints. Approximations of the K-matrix yield simple unitary descriptions of the coupled πNN-NN scattering process.

1. D. Eyre and B. J. VerWest, Phys. Rev. C 22, 664 (1980), DOE/ER/05223-24.
2. T. Sasakawa, Nucl. Phys. A203, 496 (1973); B. R. Karlsson, Phys. Rev. D 17, 642 (1978).
3. Y. Avishai and T. Mizutani, Nucl. Phys. A326, 352 (1979); A338, 377 (1980).

2. Cluster Expansions in Multichannel Scattering
(D. Eyre, J. P. Svenne and T. A. Osborn)

We have extended a recently proposed cluster expansion for the three-body problem[1] to the case of multichannel scattering. The resulting integral equations provide an approximate description of the scattering process that is accurate when clustering dominates the underlying physical states. In order to simulate a problem typical of few-body systems, we have investigated a three-body problem in which allowed asymptotic states result from elastic scattering, rearrangement, and target excitation. Specifically the system consists of three bosons of which two are identical and the third is different. These particles interact via separable interactions. We took the interaction between the two identical particles to be a two-term interaction of the Doleschall[2] type, which permits two bound states. The interactions between the non-identical particle and either of the other two were chosen to be single-term interactions of the Yamaguchi type. To check the numerical results, we compared the exact calculations using the Eyre-Osborn formulation with exact solutions from the Amado-Lovelace[3] solution, generalized to this more complicated system and solved by an entirely separate computer system. We then tested the cluster expansion technique as to convergence and sensitivity of the solutions to the details of the interaction, the positions of the inelastic and rearrangement thresholds and the ranges of the interaction. In the cases we have investigated so far we have found rapid convergence of the cluster expansion to the exact three-body solution.

1. D. Eyre and T. A. Osborn, Phys. Rev. C 20, 869 (1979).

2. P. Doleschall, Nucl. Phys. A220, 491 (1974).

3. C. Lovelace, Phys. Rev. 135, B1225 (1964).

3. Energy-Dependent Separable Potentials for the Nucleon-Nucleon Interaction

(H. Garcilazo)

Separable potentials are very useful in the numerical solution of the three-body problem because they reduce the integral equations from two continuous variables to only one. In the case of the two S-wave nucleon-nucleon channels, existing one-term separable potentials reproduce only the low-energy data; they do not produce the change of sign of the phase shifts at T_{lab} = 300 MeV. In order to be able to describe both the low-energy data and the change of sign of the phase shifts, we have constructed two models of energy-dependent separable potentials.[1]

1. H. Garcilazo, DOE/ER/05223-26.

4. Relativistic Faddeev Calculations of Pion-Deuteron Scattering

(H. Garcilazo)

The fully relativistic Faddeev equations for the three-body problem are of the form of integral equations depending on two four-dimensional relative momenta. In order to reduce the equations to a manageable form, one can eliminate in a covariant way the fourth components of the relative momenta, so that if one in addition applies the isobar or separable approximation, one obtains integral equations analogous to those of the non-relativistic three-body problem with separable potentials. We have calculated pion-deuteron elastic scattering in the region of the (3,3) resonance using two different covariant reductions of the relativistic three-body equations. We include the two S-wave nucleon-nucleon channels and the six S and P-wave pion-nucleon channels by means of separable T-matrices. We treat the spin variables relativistically by using the three-body helicity formalism of Wick.[1] Details can be found in ref. 2.

1. G. C. Wick, Ann. Phys. (N.Y.) 18, 65 (1962).
2. H. Garcilazo, Phys. Rev. Letters 45, 780 (1980), DOE/ER/05223-27.

5. The Inverse Scattering Problem with Energy-Dependent Separable Potentials

(H. Garcilazo and R. R. Wilde)

The form factors of the energy-dependent separable potentials that fit both the low-energy data and the change of sign of the phase shifts[1] have ranges in momentum space which are larger than those of the energy-independent separable potentials which fit only the low-energy data. These longer ranges are a consequence of the fact that the energy-dependent models take into account the strong repulsion at short distances. In order to show that this feature is obtained independently of the model used for the form factors, we have solved the inverse scattering problem in the case of an energy-dependent separable interaction, so that we obtain the form factors directly from the experimental phase shifts. The results of these calculations can be found in ref 2.

1. H. Garcilazo, DOE/ER/05223-26.

2. H. Garcilazo and R. R. Wilde, DOE/ER/05223-28.

6. Relativistic Effects in the Three-Nucleon Bound-State Problem (H. Garcilazo)

Relativistic effects in the three-nucleon bound-state problem are not well known although they are expected to be small since the binding energy of tritium is much smaller than its total mass. However, it is important to have exact calculations in which one can see how important these corrections really are. We have calculated the binding energy of tritium using two relativistic versions of the Faddeev equations with separable potentials, and compared them with the nonrelativistic results. We find that the relativistic effects increase the binding energy by less than 0.5 MeV. More details about these calculations can be found in ref. 1.

1. H. Garcilazo, DOE/ER/05223-30.

7. Three-Body Helicity Formalism Applied to Pion-Deuteron Scattering (H. Garcilazo)

In this work we formulate the pion-deuteron problem using a set of linear equations similar to those used in previous work, but dealing with the spin variables in a relativistic way, firstly by doing the reduction from eight to six continuous variables, taking into account the fermion propagators for the nucleons, and secondly, by performing the partial-wave decomposition of the equations using the three-body helicity formalism of Wick.[1] We use all the pion-nucleon S and P-wave channels and the nucleon-nucleon S-wave channels as input, to give a good description of the data for pion kinetic energies ranging from 142 MeV to 512 MeV. The results of these calculations can be found in ref. 2.

1. G. C. Wick, Ann. Phys. (N.Y.) 18, 65 (1962).
2. H. Garcilazo, DOE/ER/05223-31.

8. The One-Pion-Exchange Potential in Nucleon-Nucleon Scattering (H. Garcilazo)

In ref. 1 we derive the one-pion-exchange potential using the three-body model of nucleon-nucleon scattering proposed by Kloet, Silbar, Aaron, and Amado.[2] Since the standard treatment of nucleon-nucleon scattering using the idea of the exchange of mesons is based on the two-body Blankenbecler-Sugar equation, it satisfies only two-body unitarity. The three-body model, on the other hand, satisfies both two- and three-body unitarity so that it can go continuously from the region below pion-production threshold to the region above it. We find that the three-body one-pion-exchange potential has the same form as the usual Yukawa OPEP, except that its range is energy-dependent and it becomes complex above the pion-production threshold. The complete derivation of this potential can be found in ref 1.

1. H. Garcilazo, DOE/ER/05223-32.
2. W. M. Kloet, R. R. Silbar, R. Aaron, and R. D. Amado, Phys. Rev. Lett. 39, 1643 (1977).

C. Strong-Interaction Dynamics Related to NN and πN Scattering.

1. Present Status of the Pion-Nucleon Sigma Term

(C. A. Dominguez and P. Langacker)

The long-standing discrepancy between the predicted value of the πN sigma term in the framework of QCD and the value extracted from extrapolated on-mass-shell πN scattering data has been critically re-examined. Assuming the validity of the OZI rule at t=0 and using quark mass ratios extracted from the pseudoscalar meson mass spectrum one obtains the canonical result $\sigma_{\pi N} \simeq 23 \pm 5$ MeV. We argue that the possibility of readjusting the quark mass ratios to give a sigma term of 60-70 MeV so as to agree with some values extracted from πN data, is most likely ruled out. In particular this would imply a huge violation of the non-renormalization theorem in $K_{\ell 3}$ decay. Since the OZI rule is unreliable at t=0, we have recalculated the matrix element $\langle p|\bar{s}s|p\rangle / \langle p|\frac{1}{2}(\bar{u}u+\bar{d}d)|p\rangle$ using the Goldstone-boson pair mechanism and found a sigma term of 36$\pm$8 MeV. We have also examined other evidence supporting a breakdown of the OZI rule at t=0. Finally we have reconsidered the whole procedure of extracting a value of the sigma term from πN scattering data. Using the existing results on the relevant πN amplitude as a function of t and performing least-squared fits and extrapolations, we find that the sigma term is uncertain by as much as 100%, with values in the range 30-70 MeV giving equally acceptable fits to the data. We therefore conclude that both the theoretical and experimental uncertainties in the determination of the sigma term are sufficiently large for the apparent discrepancy to provide neither evidence against QCD nor against the canonical quark mass ratios that one obtains in the conventional $(3,\bar{3})$ model. For more details see ref 1.

1. C. A. Dominguez and P. Langacker, DOE/ER/05223-24.

2. Determination of the πNN, $\pi N\Delta$, and $\pi\pi\rho$ Form Factors from Quasi Two-Body Hadronic Reactions
(C. A. Dominguez)

One of the most important features of the dual-model hadronic form factor[1] is its factorization. According to this prediction the three-point function becomes a product of three ratios of gamma functions, one for each leg in the vertex. In the zero-width approximation and for each distinct leg in the vertex, the model contains one free parameter that determines the asymptotic power behavior of the form factor. These parameters may be extracted from high-energy scattering data in the Regge region.[2] The factorization property of the form factor has been tested recently[3] in connection with charged pion photoproduction, i.e., it has been shown that the form factors $F_{\gamma\pi\pi}(P_\gamma^2 = 0\ ;\ P_\pi^2 = \mu_\pi^2\ ;\ q_\pi^2)$ and $F_{\pi NN}\ (q_\pi^2;\ P_N^2 = M_N^2;\ P_N^2 = M_N^2)$ are identical when normalized to unity at the fully on-mass-shell point.

In view of the far-reaching consequences of factorization, we have tested it in the reactions $pp \to n\Delta^{++}$, $pp \to p\Delta^{+}$ and $\pi^+ p \to \rho^\circ\Delta^{++}$; these reactions provide us with three a priori different form factors, viz., $F_{\pi NN}$, $F_{\pi N\Delta}$ and $F_{\pi\pi\rho}$. In the Reggeized one-pion-exchange region the arguments of the form factors are $F_{\pi NN}\ (q_\pi^2\ ;\ P_N^2 = M_N^2\ ;\ P_N^2 = M_N^2)$,

$F_{\pi N\Delta}(q_\pi^2\,;\ P_N^2 = M_N^2\,;\ P_\Delta^2 = M_\Delta^2)$ and $F_{\pi\pi\rho}(q_\pi^2\,;\ P_\pi^2 = \mu_\pi^2\,;\ P_\rho^2 = m_\rho^2)$; i.e., all three depend only on the pion four-momentum squared and therefore according to factorization they should be identical (if normalized to the same value, e.g., unity, at the fully on-mass-shell point). A brief description of the work follows.

Differential cross sections for $pp \to n\Delta^{++}$, $pp \to p\Delta^{+}$ and $\pi^{+}p \to \rho^{\circ}\Delta^{++}$ at high energies, $p_L \approx 3\text{-}16$(GeV/c), and small momentum transfers, $0 < |t| \lesssim 0.3(\text{GeV/c})^2$, have been analyzed using a Reggeized one-pion-exchange mechanism with form factors of the monopole and the dual-model type. Results strongly confirm the dual-model prediction that $F_{\pi NN}(t) = F_{\pi N\Delta}(t) = F_{\pi\pi\rho}(t)$, when the pion is the only virtual (off-the-mass-shell) particle in each vertex and the form factors are all normalized to unity at $t = \mu_\pi^2$. No evidence has been found for non-one-pion-exchange contributions in the kinematic region under consideration, thus leading to a model independent determination of the range and asymptotic rate parameters of the three-point functions. The results are $\Lambda_\pi \approx 800\text{-}1000$ MeV and $\beta_\pi \approx 2.5\text{-}3$, in good agreement with earlier determinations from NN charge-exchange scattering and pion photoproduction. For more details see ref. 4.

1. C. A. Dominguez, Phys. Rev. D 7, 1252 (1973); D 16, 2320 (1977); R. A. Bryan, C. A. Dominguez and B. J. VerWest, Phys. Rev. C 22, 160 (1980).
2. C. A. Dominguez and B. J. VerWest, Phys. Lett. 89B, 333 (1980).
3. C. A. Dominguez and R. B. Clark, Phys. Rev. C 21, 1944 (1980).
4. C. A. Dominguez, DOE/ER/05223-25.

3. Dynamical Theory of Isospin

(R. A. Bryan)

We have continued developing a theory[1] in which isospin emerges dynamically rather than being tacked on as an afterthought. To accomplish this we conceive of elementary-particle processes as taking place in an eight-dimensional space and being governed by a generalization of the Dirac equation. As a working model we take the basic field equation for a fermion with half-integer isospin to be

$$(1) \qquad (-i\not{\partial} + m)(-i\not{\partial}' + m')\psi = V(x, x')\psi,$$

where

$$\not{\partial} = \sum_{\mu=0}^{3} \gamma^{\mu} \frac{\partial}{\partial x^{\mu}}$$

and

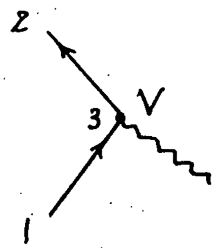
$$\not{\partial}' = \sum_{\mu'=0}^{3} \gamma'^{\mu'} \frac{\partial}{\partial x'^{\mu'}}$$

with x^{μ} $(x'^{\mu'})$ and γ^{μ} $(\gamma'^{\mu'})$ the space-time coordinates and anti-commuting Dirac γ-matrices in ordinary space-time (four-dimensional hyperspace). V represents an interaction invariant under a Lorentz (Lorentz-like) transformation in ordinary (hyper) 4-space.

The integral inversion of eq. 1 is actually the definitive equation; this inversion resembles the Bethe-Salpeter equation except that all eight coordinates refer to a single particle.

$$(2) \qquad \psi_i(x_2, x_2') = \phi_i(x_2, x_2')$$

$$- \int G_+(x_2, x_3)\, G_+(x_2', x_3')\, V(x_3, x_3')\, \psi_i(x_3, x_3')\, d^4x_3\, d^4x_3'$$



Eq. 2 may be gotten from a Lagrangian density described in ref. 1.

The free-particle solution to eq. 2 is

$$(3) \quad \psi = e^{-ip\cdot x}\, u_\pi(\vec{p})\, e^{-ip'\cdot x'}\, u'_{\pi'}(\vec{p}'),$$

where $u_\pi(\vec{p})$ $[u'_{\pi'}(\vec{p}')]$ is a Dirac spinor in ordinary [hyper] space-time and $p\cdot x = p_\mu x^\mu$ $(p'\cdot x' = p'_{\mu'} x'^{\mu'})$. In the limit where $\vec{p}' = 0$, $u_{\pi'}(\vec{p}')$ reduces to an ordinary isospinor;

$$u'^{+}_{\pi'}(\vec{p}') \rightarrow (1, 0, 0, 0) \text{ or } (0, 1, 0, 0).$$

In this limit the SU(2) - isospin matrix elements are preserved. For example, if $u'_{\frac{1}{2}}$ $(u'_{-\frac{1}{2}})$ represents the u (d) quark q and

$$V(x_3, x'_3) = (1 + \gamma_5)\gamma^\mu (1' + \gamma'_5)\gamma'^{\mu'} A_{\mu\mu'}(x_3, x'_3)$$

where $(A_{\mu 0}, A_{\mu j}) \equiv (B_\mu, W^0_\mu, W^\pm_\mu)$ represents the vector-meson quartet $(B, W^{0,\pm})$ before symmetry-breaking, then the three-point coupling constants g(q, q, W) are in the usual ratio $1:-1:\sqrt{2}$. On the other hand, for $\vec{p}' \neq 0$, isospin is automatically broken, and rather than $\vec{S}'$ (isospin) being conserved, $\vec{S}' + \vec{L}'$ ("orbital" isospin) $= \vec{J}'$ is conserved.

L' may possibly represent color (or rather, accomplish what color was invented to accomplish). A partial-wave expansion of eq. 3 in eight-space yields the solution

$$(4) \quad \psi = e^{-ip\cdot x}\, e^{-iE't'}\, j_{\ell'}(p'r')\, Y'_{\ell' m'_\ell}(\hat{r}')\, u'_{\pi'}(\vec{p}').$$

Particles with iso-angular-momentum functions $Y'_{00}\, u'_{\pi'}(\vec{p}\,')$ may represent colorless electron leptons while particles described by $Y'_{1m'_{\ell'}}\, u'_{\pi'}(\vec{p}\,')$ may represent the 3-color (u,d) quarks. Thus all the members of the first quark-lepton generation appear naturally and one does not need to invent subquarks[2,3] to reduce the number of basic particles. That is to say, through eq. 4 all the members of the first generation are just different states of a single particle.

We speculate that the second and third quark-lepton generations could be represented by higher modes of the radial functions $j_{\ell'}(p'r')$, subject to some sort of boundary condition. Projections onto Minkowski space could still be points (i.e., yield point particles in ordinary space).

1. R. A. Bryan, DOE/ER/05223-34.
2. H. Harari, Phys. Lett. 86B, 83 (1979); H. Harari and N. Seiberg, Weizman Institute of Science preprint WIS-80137 (1980).
3. M. Shupe, Phys. Lett. 86B, 87 (1979).

III. Publications Since Last Proposal (Dec. 1, 1979 - Dec. 1, 1980)

1.* "Nuclear forces," R. A. Bryan, in Encyclopedia of Physics, ed. R. G. Lerner and G. L. Trigg, Addison-Wesley, Reading, Massachusetts (1981) pp. 672-674 (ORO-5223-01)

2.* "Simple dynamical model for $\gamma N \rightarrow \pi^{\pm}\Delta$, R. B. Clark, Physical Review D 18, 1444 (1978) (ORO-5223-04, revised)

3.* "Angular dependence of $NN \rightarrow NN\pi$ cross sections and the pion form factor." B. J. VerWest, in Meson-Nuclear Physics - 1979, ed. E. V. Hungerford III, Am. Inst. Phys., New York (1979) pp. 76-77 (ORO-5223-14)

4.* "Model for off-shell form factors and application to NN Scattering," R. A. Bryan, C. A. Dominguez, and B. J. VerWest, Physical Review C 22, 160 (1980) (DOE/ER/05223-16)

5.* "Determination of the πNN vertex function from np and $\bar{p}p$ charge exchange scattering," C. A. Dominguez and B. J. VerWest, Physics Letters 89B, 333 (1980) (DOE/ER/05223-19)

6.* "Extraction of the πNN form factor from charged pion photoproduction," C. A. Dominguez and R. B. Clark, Physical Review C 21, 1944 (1980) (DOE/ER/05223-20)

7.* "Models of pseudophysical $N\bar{N} \rightarrow \pi\pi$ amplitudes," J. W. Durso, A. D. Jackson, and B. J. VerWest, Nuclear Physics A345, 471 (1980) (DOE/ER/05223-15, revised)

8. "Unitary model for the coupled πNN-NN problem," D. Eyre and B. J. VerWest, Physical Review C 22, 664 (1980) (DOE/ER/05223-23)

9. "Present status of the pion-nucleon sigma term," C. A. Dominguez and P. Langacker, submitted to Physical Review D (DOE/ER/05223-24)

10. "Determination of the πNN, $\pi N\Delta$, and $\pi\pi\rho$ form factors from quasi two-body hadronic functions," C. A. Dominguez, submitted to Physical Review C (DOE/ER/05223-25)

11. "Energy-dependent separable potentials for the S-wave nucleon-nucleon interaction," H. Garcilazo, Lettere al Nuovo Cimento 28, 73 (1980) (DOE/ER/05223-26)

12. "Complete relativistic Faddeev calculations of pion-deuteron scattering," H. Garcilazo, Physical Review Letters 45, 780 (1980) (DOE/ER/05223-27)

13. "The inverse scattering problem with energy dependent separable potentials and its application to the S-wave nucleon-nucleon interaction," H. Garcilazo and R. R. Wilde, Lettere al Nuovo Cimento (in press) (DOE/ER/05223-28)

14. "NN scattering analyses below 850 MeV: a status report," R. A. Arndt and B. J. VerWest, contributed paper to Polarization Symposium, Santa Fe, New Mexico, Aug. 11-15, 1980, and Ninth International Conference on the Few-Body Problem, Eugene, Oregon, Aug. 17-23, 1980 (DOE/ER/05223-29)

15. "Relativistic effects in the three-nucleon bound-state problem," H. Garcilazo, Physical Review C (in press) (DOE/ER/05223-30)

16. "Three-body helicity formalism applied to pion-deuteron scattering," H. Garcilazo, submitted to Nuclear Physics A (DOE/ER/05223-31)

17. "The one-pion-exchange potential in the three-body model of nucleon-nucleon scattering," H. Garcilazo, submitted to Physics Letters B (DOE/ER/05223-32)

18. "On the existence of dibaryon resonances in I=1 $^1D_2$ and $^3F_3$ nucleon-nucleon scattering," R. Bhandari, R. A. Arndt, L. D. Roper, and B. J. VerWest, submitted to Physical Review Letters (DOE/ER/05223-33)

19. "Time-reversal noninvariance in nucleon-nucleon scattering. I. General formalism and zero-range parameterization," J. Binstock, R. Bryan, and A. Gersten, accepted for publication in Annals of Physics (ORO-5223-03, second revision)

20. "Parameterization of the inelastic coupled-channel fermion-fermion scattering matrix," R. A. Bryan, submitted to Physical Review C (DOE/ER/05223-21, revised)

21. "Dynamical theory of isospin," R. A. Bryan, submitted to Nuclear Physics B (DOE/ER/05223-34)

* Cited in a previous renewal proposal