"INTERMEDIATE-ENERGY NUCLEAR THEORY"

a
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MEDIUM-ENERGY THEORY GROUP

PROGRESS REPORT

for

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"Medium-Energy Phenomenology and the Possibility
of C-Violation in the Strong Interaction"

submitted by the

TEXAS A&M RESEARCH FOUNDATION

to the

U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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Abstract

We report on research carried out during the contract period by R. A. Bryan, principal investigator, and associates R. B. Clark and B. J. VerWest. Most of the work has centered on the nucleon-nucleon interaction at low to intermediate energies and has ranged from purely theoretical studies, such as the behavior of two-pion-exchange Feynman amplitudes at far off-shell initial and final nucleon momenta, to the more practical work of phase-shift analyzing nucleon-nucleon data. We have also investigated the possibility that the NN interaction is not invariant under time-reversal and have provided predictions for some relevant experimental observables for the case where such time-irreversibility is due to short-range processes. Finally, we have completed research on topics which fall in the domain of elementary-particle physics but which we feel can lend guidance in trying to determine the NN force at very short distances; this is the current frontier in nucleon-nucleon research.

We have carried out research on a variety of topics concerning nucleon-nucleon (NN) scattering. These topics include studies of two-pion-exchange Feynman amplitudes for far off-shell initial and final nucleon momenta¹, comparison of different three-dimensional reductions of the Bethe-Salpeter equation², calculation of the pion-nucleon form factor³, parameterization of short-range time-reversal invariance violation⁴, and phase-shift analysis of NN scattering at several energies⁵. We have also worked in areas less directly related to NN scattering but potentially quite important in understanding the interaction. This includes quark-model representations of charmed mesons produced in e^+e^- annihilation, in an effort to understand production ratios⁶, and simple representations of amplitudes for the reaction $\gamma N \rightarrow \pi^\pm \Delta$ (ref. 7). The quark studies may lend guidance in our plan to represent the nucleons as free quarks in high momentum-transfer processes; and the pion photoproduction studies yield information on the $N\bar{N} \rightarrow \rho \pi$ amplitudes, useful in calculating NN $\pi\rho$ -exchange contributions. We now present the details of this research.

Pion-nucleon form factor

The original use of form factors in field-theoretical interactions was to insure mathematical solubility of the models, and the parameterization of the form factors was purely phenomenological. Now, however, there has been important progress in understanding at least the t -channel form factors. The most recent work on the pion form factor³ has given us an explanation for the somewhat greater spatial extent

of the pion-nucleon interaction as compared with the vector-meson-nucleon interaction. The u-channel form factors have also been investigated but are not presently as well understood. It seems certain, however, that while the forms of the interaction need a modification of the u-channel nature, the modifications are of much shorter range than previously supposed.

Off-shell two-pion-exchange amplitudes

The study of off-shell forms of the interaction has led to the evaluation of the two-pion-exchange diagrams for general off-shell kinematics in a dispersion-theory formalism¹. Most of the algebra has been completed and early indications are that the amplitudes may have a different off-shell form than previously obtained by arbitrary off-shell continuations of the on-shell amplitudes. Numerical and algebraic work is continuing in an effort to complete and cross-check this work.

Three-dimensional reductions of the Bethe-Salpeter equation

A comparison of unitarizing equations has been made using existing computer codes modified to solve both the Blankenbecler-Sugar equation and the Erkelenz equation². The comparison was made using the same model for the interaction in each equation and solving for the phase shifts. The predictions from the two equations differed only in the s-waves and then only amounted to a uniform shifting up or down of the plots of phase shift vs. energy. This indicates that the differences are only very short range and may be compensated for

by adjustment of the S-wave scattering lengths.

Phase-shift analysis of nucleon-nucleon scattering

Several dispersion-theoretical models for NN scattering have been recently proposed, but experimental verification of the potentials in the critical middle region ($1 - 2F$) has been lacking due to incomplete or inaccurate np scattering data in the 300 - 450 MeV range. We have nevertheless arrived at $I = 0$ (and $I = 1$) phase-shift solutions in this energy range by supplementing experiment with additional theoretical constraints⁵; these include tying the np and pp 1S_0 phase shifts together in the searches after allowing for a reasonable Coulomb correction, and fixing the $I = 0$ triplet G-wave phase-shifts at values predicted by the recent dispersion-theoretical models mentioned above. (Such models ought to be good in the high angular momentum states.) The phase shift solutions so obtained exhibit a well-defined minimum at 325 MeV, in contrast to unconstrained analyses, and the solution at the minimum interpolates well between solutions at adjacent energies. The solutions also appear to be quite reasonable from a theoretical standpoint.

We have also carried out extensive analysis of the NN data near 50 MeV (ref. 5). The main conclusion there is that the one previously-undetermined phase parameter, ϵ_1 , is well-defined when the new Davis A_{yy} data are added to the world data in the 40 - 60 MeV range.

T-violation in NN scattering

We have investigated the possibility that time-reversal and charge-conjugation invariance are violated in NN scattering, and have demonstrated

the consequences of such C- and T-violation for low to medium energies in the case where such violation is due to a very short-range interaction. The demonstration is in the form of predictions for observables which reveal T-violation (T-violation since P is assumed to be good, hence if C is bad, so are CP and T by the CTP theorem). The non-observance of an electric dipole moment for the neutron at the $3 \cdot 10^{-24}$ e-cm level rules out any possibility of C- and T-violation in the strong interaction, but such violation at the milli-strong level is still a possibility. Accordingly we parameterize the proposed T-violation by a single infinitesimal phase parameter λ_1 (λ_2) in np (pp) scattering, and then use the experimentally-known five T-symmetric Wolfenstein amplitudes to make predictions for $P - \mathcal{A}$ and $P_A - P_B$. Experimentalists are thereby guided to those angular regions where short-range T-violation, if present, will be most strongly manifest.

Amplitudes for the reaction $\gamma N \rightarrow \pi^\pm \Delta$

Non-diffractive pion-production processes are of interest not only in their own right, but also for the role that they play as intermediate states in multiple-meson-exchange contributions. During the past year we have extended our earlier investigation of $\gamma N \rightarrow \pi^\pm \Delta$, which is of particular interest due to the apparent simplicity of its dynamics. We have shown⁷ that the simplest generalization of the minimal-gauge-invariant extension of pion-exchange provides an excellent quantitative description of the unnatural-parity-exchange component of the reaction up to momentum transfer values $|t| \leq 1.4 \text{ GeV}^2$, for all charge states.

The results of this simple dynamical model compare favorably with those of the most complex Regge models which require both absorptive corrections and Regge-Regge cuts.

Quark model for charmed meson production

The possibility that observed particles are composed of more fundamental constituents offers great promise in the search for a universal description of particle interactions. There is now considerable experimental data which favor the properties ascribed to quarks for these hypothetical constituents. The recent discovery of charmed D and D^* mesons provides an excellent opportunity to increase our understanding of the simplest systems described by a quark-antiquark combination. In an effort to understand the observed production ratios for $D\bar{D}$, $D\bar{D}^* + \bar{D}D^*$, and $D^*\bar{D}^*$, we have studied the $D\bar{D}$ electromagnetic current structure in a free-quark model with constituent form factors. We have included the electromagnetic interaction with the light quarks, neglected by Glashow et al, and find that the experimental results require a substantial contribution from this component. The experimental results also show that the electric form factors must predominate over the magnetic form factors for the quarks.

Other publications

We list three other articles^{8,9,10} which have been produced or will appear during the contract period. The first⁸, "Nuclear forces", is a description of the NN interaction for non-specialists and will appear in the Encyclopedia of Physics. The third¹⁰ is a presentation

of work on the $N\bar{N} \rightarrow \pi\pi$ amplitude which has mostly been carried out prior to the contract period. The second⁹ also refers to work carried out previously.

The principal investigator, R. A. Bryan, Professor, and the other investigators, R. B. Clark, Associate Professor, and B. J. VerWest, Assistant Professor, all of the Physics Department of Texas A & M University, have each spent about 50 % of their time during the nine-month academic year on this contract. Full time is spent during the summer months as indicated in the budget.

1. B. J. VerWest, to be submitted for publication.
2. B. J. VerWest, to be submitted for publication.
3. J. W. Durso, A. D. Jackson, and B. J. VerWest, "The πNN vertex function", accepted for publication in Nuclear Physics A.
4. J. Binstock, R. A. Bryan, and A. Gersten, "Parameterization of short-range time-irreversibility in nuclear forces", submitted for publication to Nuclear Physics A.
5. R. A. Arndt and R. A. Bryan, to be submitted for publication.
6. B. Humpert and R. B. Clark, "Charmed meson production in electron-positron annihilation", SLAC-PUB-1905, submitted for publication to Physical Review D.
7. R. B. Clark, "A plebeian dynamical model for $\gamma N \rightarrow \pi^{\pm} \Delta$ ", submitted for publication to Physical Review D.
8. R. A. Bryan, "Nuclear forces", 2250-word exposition to appear in Encyclopedia of Physics, ed. Rita G. Lerner and George L. Trigg, to be published by Dowden, Hutchinson & Ross, Stroudsburg, Pa.
9. D. Geesaman, R. McGrath, P. Lesser, P. P. Urone, and B. J. VerWest, "Particle-decay of ${}^6\text{Be}$ ", accepted for publication in Physical Review C.
10. B. J. VerWest and A. D. Jackson, "Dynamics of $J = 0 \text{ } NN \rightarrow \pi \pi$ scattering for $4\mu^2 \leq t \leq 50\mu^2$ ", submitted to the Second International Conference on the NN Interaction, University of British Columbia, June, 1977.