COO-1764-322

PROGRESS REPORT

University of Minnesota

School of Physics and Astronomy

Theoretical and High Energy Physics

1976-1977

DISCLAIMER

INTRODUCTION

This Progress Report describes the research performed at the School of Physics, University of Minnesota under a U.S.E.R.D.A. basic research contract. This contract is unique, in that within the scope of a single task, research is conducted in theoretical nuclear physics, theoretical elementary particle physics and experimental elementary particle physics.

The format of this report reflects the diversity of the research. The theoretical investigations have been performed mostly by one or two investigators, often in collaboration with a similar number of colleagues from other institutions. Each investigator, therefore, has provided his own report. Experimental particle physics, however, requires the collaborative efforts of a large number of investigators, who work together in a unified effort. For this reason, a single experimental particle physics report is included.

This Progress Report covers the period October 1, 1976 through September 30, 1977.

I. Theoretical Nuclear Physics

B. Bayman

P. Ellis

Y. C. Tang

S. F. Tsai

<u>Multistep processes in two-neutron transfer reactions</u> (Ben Bayman (with M. Franey, J. Lilley, W. Phillips)).

Analysis of a two-neutron transfer reaction, such as ^{208}Pb $(^{16}O,^{18}O)^{206}Pb$ in terms of first-order distorted waves Born approximation (D.W.B.A.) implies that the transfer of the two neutrons has occurred in a single step. Testing this hypothesis is made difficult by the fact that the calculated results are strongly dependent upon the optical potentials used to generate the distorted waves, whereas these optical potentials are not uniquely determined by elastic scattering data. However, if the process takes place at subcoulomb energies, so that the oxygen and lead nuclei never get close enough to feel the nuclear part of the optical potential, then the transfer process occurs in that part of configuration space in which the distorted waves are coulomb wave functions, and no ambiguity remains. Moreover, the relative motion of the oxygen and lead nuclei at subcoulomb energies can be adequately described by semi-classical methods. Thus we have undertaken a calculation of the $^{208}Pb(^{16}O,^{18}O)^{206}Pb$ ground-state-to-ground-state transition, taking into account: 1) direct two-neutron transfer, 2) two-step transfer via the intermediate system ^{207}Pb + ^{17}O, 3) inelastic processes such as the excitation of the 3^- level in ^{208}Pb followed by direct transfer to the ground state of ^{206}Pb, or direct transfer to the first 2^+ level of ^{206}Pb, followed by de-excitation to the ^{206}Pb ground state. These indirect processes are taken into account using second-order Born approximation. The formalism has been worked out and the calculations are now in progress. Comparison will be made with extensive data taken at the Williams Laboratory.

<u>Study of the (^{3}He,^{6}He) reaction</u> (Ben Bayman (with Ali Evinay)).

We have attempted to analyze the data obtained at the Michigan State cyclotron on the ^{48}Ca (^{3}He,^{6}He)^{45}Ca reaction, using a one-step DWBA calculation. The ^{3}He wave function was taken to be $(1s)^3$, the ^{6}He to be $(1s)^4\ (1p)^2\ L = S = 0$, the ^{48}Ca ground state to be $(1f_{7/2})^8$, and the lowest $3/2^-$, $5/2^-$, $7/2^-$, $9/2^-$, $11/2^-$ and $15/2^-$ levels in ^{45}Ca to be associated with the $(1f_{7/2})^5$ configuration. The calculated shapes of the angular distributions for the $3/2^-$, $5/2^-$, $7/2^-$ and $15/2^-$ levels agree with experiment, but not those of the $9/2^-$ and $11/2^-$ levels. The calculated relative cross-sections for the different levels are in poor agreement with experiment, except for the lowest two levels ($7/2^-$, $5/2^-$). Thus either the higher levels of ^{45}Ca are poorly described by the $(1f_{7/2})^5$ configuration, or the (^{3}He,^{6}He) reaction populating these levels proceeds by a more complicated mechanism than we have assumed. Analysis of data taken with other targets may shed light on these questions.

This calculation was part of the Ph.D. Thesis of Ali Evinay.

<u>Wave function for the 6-quark deuteron</u> (Ben Bayman (with A. N. Mitra)).

Six-quark deuteron wave functions have been constructed which are totally antisymmetric with respect to the interchange of position, spin isospin and color of any pair of quarks, and totally antisymmetric with respect to the interchange of position, spin and isospin of the two nucleons. Explicit forms are obtained for wave functions which transform irreducibly with respect to operations of SU_4 in charge-spin space, and SU_3 in color space. These wave functions have been obtained by diagonalizing appropriate Casimir operators. They are being used in analyses of elastic and deep-inelastic e-d scattering.

A summary of this work appeared as an abstract at the International Conference on Nuclear Structure held in Tokyo, September 1977.

Study of the (α,p) reaction (B. Bayman (with Ali Evinay)).

This reaction has been treated in the distorted waves Born approximation, using Wood-Saxon wells for the nuclear bound states. The method of transforming to relative coordinate of the three transferred nucleons is a generalization of the one developed for the two-nucleon problem by Bayman and Kallio. A detailed analysis has been performed of some recent data taking at the Niels Bohr Institute in Copenhagen on the $^{45}Sc(\alpha,p)^{48}Ti$ reaction.

The ground state of ^{45}Sc was assumed to be dominated by the $(1f_{7/2})^5$ configuration. Some of the low-lying even-parity levels of ^{48}Ti are dominated by the $(1f_{7/2})^8$ configuration, and their (α,p) strength is given well by our calculation. Exceptions are the two 6^+ levels at 3.329 MeV and 3.507 MeV, which are populated in the ratio of 1 to 5, whereas we calculate (using $(1f_{7/2})^8$ wave functions) that they should be equally populated. This indicates that one or both of these levels is considerably affected by configuration mixing. The odd-parity levels of ^{48}Ti involve excitation of nucleons out of the (2s 1d) core or promotion of nucleons to the (3s 2d 1g) shell. Although no shell-model calculations have been done for these levels, we have done some (α,p) calculations for simple representative configurations. We conclude that the falling cross-section at forward angles seen in the odd-parity transitions is due to $L = 2$ transitions.

More data are being taken, and we will continue our collaboration with the Copenhagen group.

This calculation was part of the Ph.D. thesis of Ali Evinay.

<u>Coupling of a nucleon to a rotating core</u> (B. Bayman (with R. Falkenberg)).

An important feature of the description of rotational nuclei is the behavior of a nucleon moving in the deformed potential provided by the other nucleons. In the standard Nilsson treatment of this problem, the deformed potential is regarded as fixed in space, and thus the Schrodinger equation involves only the position and spin degrees of freedom of the nucleon. Single-nucleon states calculated in this way are used to construct the intrinsic state, on which the rotational band is built. However, the deformed potential is really not fixed in space, and the problem of a nucleon moving in this potential involves the orientation degrees of freedom of the potential as well as the position degrees of freedom of the nucleon.

This problem is solved by making the following expansion of the wave function:

$$\Psi^{I}_{M}(\alpha\beta\gamma, \vec{r}\,'\sigma') = \sum_{n\ell j K} C^{I}_{n\ell j K} \Big[\overset{*}{D}{}^{I}_{MK}(\alpha,\beta,\gamma)\, \phi^{n\ell j}_{K}(\vec{r}\,',\sigma') + (-1)^{I-K}\, \overset{*}{D}{}^{I}_{M\,-K}(\alpha,\beta,\gamma)\, \phi^{n\ell j}_{-K}(\vec{r}\,',\sigma') \Big]$$

Here I is the total angular momentum of the state and M is its component along a space-fixed z-axis. α,β,γ are the Euler angles of a body-fixed coordinate system, which determines the orientation of the potential. $\vec{r}\,', \sigma'$ locate the nucleon and its spin with respect to these body-fixed axes. $\phi^{n\ell j}_{K}$ are harmonic oscillator eigenstates. This wave function is substituted in the Schrodinger equation to determine the coefficients $C^{I}_{n\ell jK}$.

In the Nilsson model with an axially symmetric potential, the only mixing is in $n\ell j$, and this is produced by the deformation. K is a good quantum number and the $C^{I}_{n\ell jK}$ are independent of I for a given rotational band. In our more complete calculation, which takes into account the Coriolis coupling, we get mixing in K as well as in $n\ell j$, and the $C^{I}_{n\ell jK}$ depend upon I. For a strongly deformed nucleus, the deviations from Nilsson's results are small, but they become appreciable in situations where the off-diagonal matrix elements of the Coriolis coupling is comparable to the difference between Nilsson energies.

The above wave function is also applicable in the limit in which the potential has no deformation. Then the coefficient $C^{I}_{n\ell jK}$ becomes proportional to the vector-coupling coefficient $(LJ0K|IK)$, where L is the orbital angular momentum of the core. Thus we have been able, in a single representation, to follow the transition from very strong to very weak deformation.

This calculation formed the basis of the Master's thesis of R. Falkenberg. Its results are being prepared for publication.

Systematic Investigation of Scattering Problems with the Resonating-Group Method (Y. C. Tang (with M. LeMere and D. R. Thompson)).

The method of the resonating-group structure or the resonating-group method (RGM) is a microscopic method which takes cluster correlations explicitly into consideration. It has the following important characteristics:

(i) It employs totally antisymmetric wave functions and, therefore, takes the Pauli exclusion principle fully into account.

(ii) It utilizes a nucleon-nucleon potential which explains reasonably well the two-nucleon low-energy scattering data.

(iii) It treats correctly the center-of-mass motion of the entire system.

(iv) It considers nuclear bound-state, scattering, and reaction problems from a unified viewpoint.

(v) It can be used to study cases where the particles involved in the incoming and outgoing channels are arbitrary composite nuclei.

The purpose of this investigation is to test the utility of this method by making a systematic study of the $\alpha + \alpha$, $N + \alpha$, $N + {}^{16}O$, and $N + {}^{40}Ca$ systems. The nucleon-nucleon potential employed contains a weakly repulsive core and yields a satisfactory description of not only the two-nucleon low-energy scattering data but also the essential properties of the deuteron, triton, and α particle. The result shows that the calculated values do generally agree quite well with experimental data. In particular, it is found that, because of the use of totally antisymmetric wave functions, the scattering behavior at large angles is adequately described.

From these calculations one can also examine the effects of the Pauli principle. The result of this examination shows that this principle has generally an important influence and must always be taken into consideration in nuclear scattering problems.

Complex-Generator-Coordinate Technique in Resonating-Group Calculations (Y. C. Tang (with M. LeMere and D. R. Thompson)).

Because of the necessity to use a totally antisymmetric wave function and to correctly treat the center-of-mass motion, complicated matrix elements occur in resonating-group calculations when the number of nucleons involved is large. To facilitate the computation of these matrix elements, we have recently developed a complex-generator-coordinate technique. In this technique, the essential idea is to express the resonating-group trial wave function as an integral of two-center shell-model functions, with the centers of the potential wells located at complex spatial points, and then make use of techniques in shell-model calculations to carry out an analytic evaluation of these matrix elements. Using this technique, we have successfully carried out a number of calculations for relatively heavy systems where the clusters are described by flexible internal wave functions. In fact, it is anticipated that even very heavy systems, such as $\alpha + {}^{208}Pb$ scattering, can be studied by employing this technique, thus greatly extending the usefulness of the resonating-group method in treating scattering and reaction problems.

Odd-even Behavior in the $n + {}^{6}Li$ System (Y. C. Tang (with D. J. Stubeda)).

In this investigation, we have examined the elastic scattering of neutrons from ${}^{6}Li$ with the one-channel resonating-group method. A phenomenological imaginary potential was used to approximately account for reaction effects. The result shows that, by adjusting only the depth parameters in the imaginary potential, a good agreement with experiment for both the differential scattering and the total reaction cross sections can be obtained.

In addition, we have studied the effect of the Pauli principle on the odd-even nature of the effective internuclear potential. The results of this study lead us to the conclusion that the blocking effect, arising from the two nucleons in the nonclosed 1p shell of the ^{6}Li nucleus, is very important. It is responsible for the different behavior in the two channel-spin states; that is, the effective potential for $s = 1/2$ is found to be stronger in odd-ℓ states than in even-ℓ states, while the opposite is true for $s = 3/2$.

The blocking effect is also responsible for the finding that the odd-even characteristic in the n + ^{6}Li system is not as pronounced as that in the n + α systems. As a consequence of this, there exists only a moderate rise in the n + ^{6}Li differential cross section in the backward angular region. In fact, it is found that at 30 MeV the backward-to-forward ratio $\sigma(180^0)/\sigma(0^0)$ for the n + ^{6}Li system is smaller by an order of magnitude than that for the n + α system.

Effective Operators in the Shell Model (P. J. Ellis).

The "tutorial-style" review article on effective operators, mentioned in the progress report and proposal last year, is in the publication stage. This article gives a non-rigorous, intuitive discussion of the formalism and a fairly comprehensive summary of the calculations to date (with E. Osnes, Stony Brook and Oslo).

We have studied the cancellation of the number conserving sets for the effective charge by generalizing the unperturbed particle-hole states to Tamm-Dancoff approximation (TDA) phonons and by replacing the bare operator by an effective operator consisting of the bare plus TDA contributions. For the sum of the first set (diagrams 4-7 of Ellis and Siegel, Phys. Lett. 34B, 177 (1971) we find for neutrons a change of sign and a somewhat larger magnitude compared to second order. For protons the sign remains negative and the magnitude increases by 50%. Replacing the oscillator basis by a simulated Hartree-Fock basis, according to our earlier work, the cancellation for neutrons is improved compared to the second order oscillator result. For protons the net result is similar to second order. For the second number-conserving set (diagrams 8-13 of the above reference) the results are qualitatively little changed from second order. There appear to be no strong correlation effects in the diagrams considered, which include a class of renormalizations not hitherto examined. These diagrams can therefore probably be neglected in trying to construct a theory of effective charges (with F. L. Goodin, Minnesota graduate student).

We have studied numerically a technique for obtaining linked effective interactions using matrix techniques which differs from that originally proposed (publication COO-1764-217). Good agreement between the two methods is obtained for closed shell and closed shell plus one nuclei, but we have not yet been able to generalize the second method to closed shell plus two nuclei (with J. C. Collett, graduate student). We note that the proposed study of the A = 4 - 6 systems by the original technique has been dropped as P. R. Goode (Rutgers) was unable to complete the calculations before leaving the field.

Heavy Ion Reactions (A. Dudek-Ellis and P. J. Ellis).

a) The $^{28}Si(^{19}F,^{16}O)^{31}P$ Reaction at 60 MeV.

Data was taken here at Minnesota for this reaction and for the $^{30}Si(^{19}F,^{16}O)^{33}P$ reaction which shows similar features. Comparison with finite-range DWBA calculations (using the no-recoil approximation in most cases) showed that the predictions for the angular distributions of the $1/2^+$ and $3/2^+$ levels of ^{31}P were completely out of phase with the data. The prediction for the $5/2^+$ angular distribution was similar to that of the $3/2^+$ case, since the optical parameters were spin-independent so that there were only minor differences in the calculations. By contrast the $5/2^+$ data showed a smooth fall-off with angle compared to the strong oscillations seen in the $3/2^+$ data. The theoretical predictions were not improved by allowing inelastic scattering between members of the ^{19}F ground state rotational band in a CCBA calculation. We therefore refitted the elastic entrace channel data including a spin-orbit potential $\underline{\ell}\cdot\underline{s}$ of standard form and strength 3 MeV. In the exit channel we included an $\underline{\ell}\cdot\underline{I}$ component, where I refers to the spin of ^{31}P, with a strength of 3/4 MeV. Since there was no data here, we demanded that the spin dependent and spin independent (taken from $^{16}O + {}^{32}S$ work) parameters predict approximately the same elastic angular distribution. Using these optical parameters, it was found possible to obtain a good fit to all the reaction data. This is qualitatively similar to earlier (α,p) work, however, rather little is known about spin dependent forces for heavy ions so that further experimental work is to be desired. This work is published in Phys. Rev. Lett. 38, 817 (1977) (in collaboration with the Minnesota experimental group).

b) The ^{30}Si(^{16}O,^{16}O$'$) reaction at 60 MeV (A. Dudek-Ellis).

The Minnesota elastic scattering data for ^{16}O + ^{30}Si shows pronounced oscillations starting at about 50^{o}; accurate data out to 77^{o} is also available for inelastic excitation of the 2^+ level of ^{30}Si. We have attempted to fit this data in a coupled channels calculation using either the macroscopic rotational or vibrational model. It was not found possible to fit the phasing of the oscillations for both the 0^+ and 2^+ angular distributions simultaneously. Both small and standard imaginary diffusivities (i.e., 0.2 and 0.7) were tried and also coupling to the 4^+ level was considered. We did find some improvement by including an $\underline{\ell}\cdot\underline{I}$ term in the optical potential, but the fit was not satisfactory (with D. Dehnhard and V. Shkolnik, Minnesota).

c) ^{40}Ca(^{13}C,^{14}N)^{39}K reaction at 60 and 68 MeV (B. F. Bayman, A. Dudek-Ellis and P. J. Ellis).

This reaction to the ^{39}K ground state and $1/2^+$ first excited state provides perhaps the prime example of a case where the DWBA predictions are out of phase with the data. We first investigated the effect of re-orientation terms arising from the quadrupole moments of ^{14}N and ^{39}K; only very small changes were produced in the angular distribution. We then investigated the effect of spin-orbit components in the optical potentials and found that it was possible to shift the phase of the DWBA predictions (in the no-recoil approximations) into agreement with the data, while maintaining a fit to the elastic data. Spin-orbit potentials of standard form were used with strengths of 3 MeV for the $\underset{\sim}{\ell} \cdot \underset{\sim}{s}$ term acting on ^{13}C and ^{14}N and 1 MeV for the $\underset{\sim}{\ell} \cdot \underset{\sim}{I}$ term acting on ^{39}K (c.f. part a) above). We also investigated the non-anomalous $^{40}Ca(^{13}C,^{12}C)^{41}Ca$ reaction; predictions for the phasing were reasonable when spin-orbit potentials were included, but the damping of the magnitude of the oscillations was disturbing. The results obtained were understood by generalizing the Strutinsky model (Sov. Phys. JETP 19 (1964) 401), for reactions localized around a large angular momentum, to include the effect of the various spins involved. It was found that the oscillations in the cross section arose from interference between opposite relative orientation of the intrinsic spins with respect to the orbital angular momentum. This is particularly transparent for the $^{28}Si(^{19}F,^{16}O)^{31}P$ ($1/2^+$) reaction of part a) where there are just two channels—one with the spins of ^{19}F and ^{31}P both parallel to the relative orbital angular momentum, and the other with them both antiparallel. Now the important quantity is the difference in phase between the S-matrix elements in the two cases, each taken at the peak of $|S|$. In the absence of spin-orbit potentials this phase difference is 180^o, but by introducing spin-orbit effects it was reduced to 37^o and hence the predicted oscillations were brought into phase with the data. This work has been submitted for publication.

A Unified Approach for Calculating the Nuclear G-matrix (S. F. Tsai).

Following a method proposed earlier by Tsai and Kuo, we show that nuclear G-matrix elements defined with orthogonalized plane-wave and harmonic-oscillator intermediate states can both be evaluated conveniently and exactly using the same approach.

Coordinate-space Formalism of the Random-phase Approximation (S. F. Tsai).

Based on the conventional particle-hole representation of the random-phase-approximation eigenvalue equation, it is shown that coordinate-space formalism can be derived directly and is valid generally for rotation and time-reversal invariant interactions. Explicit expressions are given for the interaction strengths and transformation coefficients in the case of Skyrme interactions.

On the Validity of a Model for Deep Inelastic Reactions (S. F. Tsai and G. F. Bertsch).

We show that within the DWBA theory less than 25% of the deep inelastic proton scattering cross-section on ^{208}Pb at E_p = 62 MeV can be accounted for by direct one-step excitations of the target nucleus in an independent-particle model. A previous calculation which agrees well with the experimental result using this model probably has erred by misinterpreting the excitation strength amplitude $\beta_L(E)$ to make it about $(2L+1)^{\frac{1}{2}}$ times larger.

On the Recursive Computation of an Integral involving the Generalized Laguerre Polynomials (S. F. Tsai).

The technique of backward recurrence is shown to apply to an integral arising from the nuclear G-matrix equation and involving the product of two generalized Laguerre polynomials.

II. Theoretical Elementary Particle Physics

S. Gasiorowicz

D. Geffen

J. Rosner

H. Suura

W. J. Wilson

Encyclopedia Article (S. Gasiorowicz).

I was asked to write a survey of elementary particle physics which would serve as an overall guiding article for 20 - 30 shorter contributions to the Encyclopedia of Physics. The survey covers the following topics: (a) Classification of Particles; (b) Classification of Interactions: The electromagnetic interactions, the weak interactions, the unification of the electromagnetic and weam interactions, the strong interactions; internal symmetries, Regge Poles, Multiparticle Processes and Diffraction; Duality; (c) Quarks as Fundamental Particles; (d) Hadronic Weak Interactions and Current Algebra; (e) Deep Inelastic reactions and Asymptotic Freedom; (f) Quantum Chromodynamics; (g) Electron-positron annihilation and the New Particles.

On the Lipatov Method (S. Gasiorowicz).

Recently much attention has been attracted by work of L. N. Lipatov on the structure of large-order terms in perturbation expansions of Green functions. The basic approach is to express the Green function in terms of a functional integral in Euclidean space, and then to project out the n-th order term in the expansion. For the vacuum functional, for example,

$$\sum C_n g^n = \int [d\phi]\, e^{-S_E(\phi, g)}$$

implies

$$C_n = \frac{1}{2\pi i} \oint \frac{dg}{g} \int [d\phi]\, e^{-S_E(\phi, g) - n \log g}$$

This functional is evaluated by finding joint saddle points in the field variable (classical solutions) as well as in the coupling constant space. An important result obtained by E. Brezin et.al. is that the perturbation series is Borel-summable if the field is expanded about a stable vacuum. If the theory has real pseudoparticles (as the Yang-Mills theory does) then the series is not Borel summable.

In collaboration with H. Abarbanel of Fermi National Laboratory I studied the question of the convergence of the expansion for the vacuum functional in a series in a parameter h that is a function of g. The procedure followed was

(1) The fields were rescaled so that the action took the form

$$S_E = \frac{1}{g} A(\psi)$$

(2) The quantity of interest is D_n, defined by

$$\int [d\psi] \, e^{-A(\psi)/g} = e^{-A(\psi_c)/g} \sqrt{g} \sum D_n h^n$$

where

$$\left(\delta A / \delta\psi\right)_{\psi_c} = 0$$

and it is expressed as

$$D_n = \oint \frac{dh}{2\pi i h} \int [d\psi] \, e^{-[A(\psi) - A(\psi_c)]/g} \frac{e^{-n \log h}}{\sqrt{g}}$$

(3) The form of h must be such that for n large, the Gaussian approximation dominates the expansion of the exponential in the above expression. Thus for the general relation $G = A H^{\alpha}$, where $G = \log g$ and $H = \log h$, it turns out that

$$1 < \alpha < 3$$

It turns out that for α in that range the series is convergent.

The procedure turns out to be practically useless, since there is no way of calculating the small n terms reliably. What it does show is that the series obtained by the Lipatov method need not have the same analyticity properties in the parameter g as the original function: the series is convergent for all α in the allowed range, yet the function clearly cannot be analytic for all the α values. The results of this study were somewhat disappointing, and it was decided not to publish them.

Derivation of quark-confinement equation in Hamiltonian Formalism of gauge field theories (H. Suura).

I derived the one-time relativistic wave equation for a gauge independent amplitude

$$\chi(1,2) = \left(\Psi_0,\ e^{ig\int_1^2 \vec{A}(x)\cdot d\vec{x}}\, q(1)\, q^+(2)\, \Psi\right), \tag{1.1}$$

where q(x) is the quark field and $\vec{A}(x)$ is the vector potential in the spatial gauge $A_0 = 0$. I take the equal-time plane $t_1 = t_2$ in the rest frame of the system and choose as the integration path a straight line connecting 1 and 2. I emphasize that the amplitude (1) is essentially different from the Bethe-Salpeter amplitude because (1) would vanish if Ψ is a normal state involving only a finite number of photons, like a positronium state. (1) is specifically suited to describe a confined state of a quark and an anti-quark connected by a linear electric flux. In order to make a resulting Brillouin-Wigner series for the potential finite, I introduce the radius a of the electric flux, by modifying the straight line integral in (1) into a bundle of line integrals connecting 1 and 2 and lying in a sausage-shaped tube of radius a. The resulting equation is

$$(-i\alpha\cdot\nabla_1 + \beta m)\,\chi(1,2) + \chi(1,2)(-i\alpha\cdot\overleftarrow{\nabla}_2 - \beta m)$$

$$= [M - V(\vec{r})]\,\chi(1,2), \tag{1.2}$$

where the potential consists of a confinement potential k^2r with $k^2 = g^2/8\pi a^2$ plus a well-defined Brillouin-Wigner series, which are defined in terms of the renormalized coupling constant g_r. I find rigorously $V(0) = 0$, and infer generally in the static limit

$$V(r) = k^2 r - \frac{g_r^2}{4\pi} \frac{C(r/a)}{r} \tag{1.3}$$

where $C(x) \sim x^2$ $(x \to 0)$, and $C(\infty) < \infty$. It is suggested that the confined state exists for $g_r^2/4\pi > 2$, whereas for $g_r^2/4\pi < 2$ the positronium state is more stable. It is also proposed that a be treated as a dynamical parameter to be determined so as to make the energy minimum. (Submitted to Phys. Rev. D).

Gauge-independent two-body amplitude and vector dominance model of electromagnetic form factors (H. Suura)

Under the assumption that color triplet states have infinite energies (or correspondingly in QED the assumption that states with quark number ± 1 have infinite energies), I have shown that the amplitude (1) vanishes unless $t_1 = t_2$. This result may be stated as

$$\chi_p(1,2) = \delta(p \cdot (x_1 - x_2))$$

where p is the 4-momentum of the state. It follows that the electromagnetic vertex $\iint \bar{\chi}_{p'}(1,2)\, \gamma_\mu\, \chi_p(1,2)\, d^4x_1\, d^4x_2$ vanishes unless $p' = p$. On the other hand the 3-meson vertex is given by an overlap integral

$$\iiint d^4x_1\, d^4x_2\, d^4x_3 \quad \delta(p_1\cdot(x_1-x_2))\ \delta(p_2\cdot(x_2-x_3))$$
$$\times\ \delta(p_3\cdot(x_3-x_1))$$

which is non-vanishing. This gives the basis for the vector dominance model of the electromagnetic form factors. VDM does not apply to inelastic processes involving more than two hadrons. (Phys. Rev. Letters 38, 927 (1977)).

3. Relativistic Two-body equation and meson spectrum (H. Suura).

The relativistic equation (1.2) has a singularity at $r = R$ such that $V(R) = M$ (mass eigenvalue) which happens if $V(r)$ contains a linear potential. The equation is infested with the so-called Klein-paradox, because we have an effective negative potential $-\frac{1}{4}V(r)^2$ as $r\to\infty$. I proposed to obtain an eigenvalue problem out of (1.2) by requiring (a) local normalizability and (b) outgoing wave condition at infinity. The former condition alone gives a unique boundary condition at $r = R$, which, coupled with the ordinary boundary condition at $r = 0$, determines the eigenvalue and eigenfunction inside R. The two conditions applied to the region $r \geq R$ require $\chi(1,2) = 0$ there. Thus, I arrived at a kind of bag picture of the hadrons. A preliminary analysis of the equation (1.2) was made without specifying $V(r)$ for π, ρ, A_1 and B mesons. I found that the eigenvalue problem for ρ is given by two coupled second order differential equations for two amplitudes, which involve $L = 1$ centrifugal barrier. Thus, ρ meson mass is raised without spin-spin interaction. I also showed that there are two branches of solutions, which I identified with ρ and ρ'. (Phys. Rev. Letters 38, 636 (1977)).

Solutions to a Gauge-Invariant Equal Time Two-Body Wave Equation; The Light Mass Quark-Antiquark System (D. A. Geffen and H. Suura).

The properties of solutions to the two body wave equation proposed by Suura (see eq.(1.2) above) have been examined in detail for the case of a confining potential. (i) Because the potential is confining, the conditions of local normalizability and outgoing waves at infinity require, uniquely, bag type solutions that vanish outside a sphere of radius fixed by the mass eigenvalue of the state. A flux density has been defined satisfying an equation of continuity. We find that the bag boundary conditions yield everywhere a finite and continuous flux density for all possible states. (ii) In the limit of vanishing quark mass, chiral symmetry is spontaneously broken for the J = 0 and only the J = 0 states. This occurs because of the bag boundary condition. The pion, in general, has an appreciably lower mass than its chiral partner, a 0^{++} meson. Degenerate chiral partners appear for all the $J \geq 7$ states. The A_1-trajectory $(C = P = (-1)^{J+1})$ is degenerate with the ρ-trajectory $(C = P = (-1)^J)$, while the B-trajectory $(C = -P = (-1)^J)$ is degenerate with the ρ'-trajectory $(C = P = (-1)^J)$, the latter system being the higher mass trajectory split from the ρ-trajectory because of the mixing of $^3(J\pm1)_J$ states.

In an exact theory, the Nambu-Goldstone theorem requires that the pion mass vanish if chiral symmetry is spontaneously broken. We have found numerical solutions to equation (1.2) using as a model for the potential,

$$V(r) = k^2 r - \frac{g_r^2}{4\pi} \frac{r}{r^2+a^2} \quad . \tag{1}$$

Solutions with a zero mass pion can always be found by a suitable choice for a as long as $g_r^2/4\pi$ is greater than the critical value 2.

(iii) Using eq. (1), the mass spectra for the ρ , A_1, and B-trajectories have been calculated as a function of quark mass m, k^2, g_r^2, and a. For 300 MeV $\leq m \leq$ 500 MeV, remarkably good fits to the observed I = 1 meson spectra can be obtained for ranges of values of g_r^2 and k^2. When the parameter a is chosen to make the pion mass vanish when $m \rightarrow 0$, it turns out to be very small so that all the other mass eigenvalues are insensitive to its value (alternative modes for treating a are being examined). The $\rho(773)$, $A_2(1310)$, g(1690), B(1230), and $\delta(976)$ (assumed to be 0^{++}) masses can all be fit to better than 5%. The A_1 meson ($^3P_1$, 1^{++} state) is found to exist with a mass in the neighborhood of 1100 MeV. The expected splitting scheme for the ^3P states is verified with

$$M_\delta < M_{A_1} < M_{A_2}$$

so that our model does not seem compatible with an A_1 mass of 1450 MeV as proposed by several authors who have analyzed hadron production data. The clear $\pi\rho$ enhancement, recently reported by both SLAC and DESY as probably arising from the heavy lepton decay: $\tau \rightarrow \nu + \pi + \rho$, strongly suggests an A_1 meson with a mass of about 1150 MeV. This comes remarkably close to our prediction.

Our model potential favors values of $g_r^2/4\pi$ in the range between 2.2 and 2.5, in contrast to values $g_r^2/4\pi < 0.4$ obtained for non-relativistic charmonium models. We observe that these two different values are not incompatible when we take into account the fact that $g_r^2/4\pi$ is an effective coupling constant which depends on the average momentum transfer in the quark-antiquark system. Since much smaller momentum transfers occur in the light mass system than in the heavy charmed quark system, a large increase in $g_r^2/4\pi$ is expected (QCD, at present, cannot reliably estimate the increase). (Accepted for publication in the Physical Review D).

<u>Implication of new set of resonance photocouplings</u> (J. Rosner (with J. Babcock, R. Cashmore, and A. J. G. Hey)).

Work done previously with J. Babcock[1] was updated in collaboration with the last-named two authors in the light of baryon resonance photocouplings[2] for which probable errors have been estimated. The conclusions remain[1] that the relative phase of F-wave and P-wave πN couplings in the <u>56</u>, L = 2 multiplet disagrees with that obtained[3] from $\pi N \to \pi\Delta$,[4] implying that a re-examination of the $\pi N \to \pi\Delta$ phases may be worthwhile. Other possible interpretations of this discrepancy also were offered:[5] uncertainties in the photocouplings themselves, mixing between <u>56</u> and <u>70</u> L = 2 multiplets, or the possible inadequacy of the single-quark $SU(6)_W$ analysis itself.

<u>Isospin restrictions on charmed particle decays</u> (with M. Peshkin).

This work, described in part previously,[1] was completed.[6] The restrictions imposed by isospin on charge distributions in decays like $C_0^+ \to \Lambda 3\pi$, $D \to \bar{K}$ + pions, etc. were described, and consequences of a statistical postulate[7] were given.

<u>Tests for CP violation in charmed particle decays</u> (with M. Goldhaber).

This work, described in part previously,[1] was completed.[8] Tests were described of CP selection rules in the reactions $e^+e^- \to D^0 \overline{D^0} + m(\pi^0) + n(\gamma)$ and in the subsequent decays of the neutral charmed mesons to eigenstates of CP. It was shown that a signal for CP violation is easier to detect when the two charmed mesons decay to <u>different</u> CP eigenstates.

Final states in decays of heavy particles (in part with C. Quigg).

Several items related to this topic (described in part previously[1]) were completed.[9-11] A statistical model for charmed particle decays was treated at some length,[9, 11] and compared with present data. Predictions were presented for branching ratios into specific semileptonic and nonleptonic channels. Suggestions were made for best channels in which to observe both the charmed-strange F meson,[9, 11] and the pseudoscalar $c\bar{c}$ states η_c and η_c'.[10] Specific ways in which decays like $D^+ \to \bar{K}^0\pi^+$ could resolve questions of nonleptonic enhancement were pointed out.[9]

Improved lower limits on neutral fermion masses.

The apparent suppression of parity violation in atoms below the level predicted by the Weinberg-Salam model[12] can be dealt with by postulating a new heavy neutral fermion N coupled right-handedly to the electron via the standard charged weak current.[13] Existing lower limits on the mass of this lepton came from the absence of $K^+ \to Ne^+$: $m_N > \frac{1}{2}\ GeV/c^2$.[14] However, it was shown that the absence[15] of any prominent signal for N in the decays of the charged heavy fermion τ,[16] $\tau \not\to N e \nu_\tau$, allows one to improve this bound to $m_N \gtrsim 1\ GeV/c^2$.[17] A systematic search for $F \to Ne$, if indeed $m_F \simeq 2\ GeV/c^2$,[18] should allow this bound to be further raised to about $1\frac{1}{2}\ GeV/c^2$ if no signal is seen.[9, 17]

Potential models for bound states of heavy quarks (with C. Quigg).

It appears that the new heavy meson Υ[19] has an excited state Υ'[20]

with $m(\Upsilon') - m(\Upsilon) \simeq m(\psi') - m(\psi)$. It was found that the sole potential for which this equality is not an accident is $V(r) = C \ln (r/r_0)$.[21] Consequences of this potential for the ψ and Υ families were enumerated, and compared with results from the more popular combination of a Coulomb and a linear potential.[22] As a result of these studies, several simple scaling laws for level spacings E and for squares $|\Psi(0)|^2$ of S-wave wave functions at the origin, as functions of the particle mass and principal quantum number, were derived. These will be presented in a separate publication.[23]

Applications of non-associative algebras to unified theories of particle interactions.

During the author's stay at the Institute for Advanced Study the work by Gürsey and collaborators[24] on the role of octonions in particle physics was reviewed and applications sought to the problems of quark and lepton classification and of quark confinement. It was the author's opinion at the conclusion of this work that the spectrum of quarks and leptons and the structure of the weak gauge group were sufficiently uncertain at present that no conclusive tests of the classification aspect could be made. The quark-confinement problem was also found to be intractable from the octonionic point of view, since it was not expected to be a short-distance phenomenon, while octonionic quantum mechanics presumably makes statements about the shortest distances.

An effort was begun in collaboration with R. Slansky and M. Gell-Mann to graft an octonionic structure onto certain supersymmetries. The work is still in progress.

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Progress Report (Warren J. Wilson).

During the last year my time has been more or less evenly divided between two projects. The beginning of the year was spent on an analysis of the semileptonic decays of charmed (D) mesons with particular attention focussed on the energy spectrum of the final lepton. This work resulted in the publication of my paper, "Lepton spectrum in the semi-leptonic weak-decays of charmed mesons" (Phys. Rev. D16, p. 742 (1977)). The remainder of my time was spent collaborating with H. Suura and D. Geffen on the analysis of the relativistic two-body wave equation proposed by Suura to describe the properties of mesons.

At present I am continuing my collaboration with Suura and Geffen. Also, I am considering the possibility of extending my work on the decays of charmed meson to include Ke correlations, and perhaps also purely leptonic decays.

III. Experimental Elementary Particle Physics

H. Courant

M. Marshak

E. Peterson

K. Ruddick

Y. I. Makdisi

Progress Report - High Energy Physics (H. Courant, Y. Makdisi, M. Marshak, E. Peterson and K. Ruddick).

The experimental group has continued its program of studying strong interactions with both unpolarized and polarized beams at the Argonne Zero Gradient Synchrotron. In addition, a Fermilab experiment on the electromagnetic couplings of vector mesons is currently being installed in the Meson Laboratory Ml beam line. Highlights of the past year's activities include:

--Analysis of a high-resolution, high statistics elastic scattering experiment (E-365) indicated previously unknown cross-section fluctuations in πp elastic scattering and showed that parton models fail in their detailed predictions for large t elastic scattering cross-sections as a function of incident energy.

--An experiment on p-^{4}He elastic scattering at incident kinetic energies near 1 GeV has reported a definitive set of cross-sections and the first polarization measurements in this energy range. These data have already been used by several theorists to study nucleon-nucleon amplitudes and nucleon-nucleus scattering models.

--Data have been recorded on pn elastic scattering polarizations at large angles at incident momenta of 2, 3 and 6 GeV/c. Analysis of this experiment is currently in progress.

--An exhaustive experiment has been completed to search for direct electron production at incident momenta between 3 and 12 GeV/c in pp collisions. A variety of incident momenta, production angles and targets have been used. The results are consistent with zero direct electron production after the subtraction of vector meson effects. The level of direct electron production is significantly lower than that reported in a previous experiment by another group.

The status of all currently active experiments is listed in Table 1 in the chronological order of the proposals. The following discussion of the experimental program is organized by subject without regard to the chronology.

Elastic Scattering

Of all the processes that can occur in high energy hadron collisions, elastic scattering is the single most likely. Even at very high energies, when hundreds of inelastic channels are open, the elastic channel still accounts for about a quarter of the total cross-section. Because of their importance elastic processes have been extensively studied. Still many questions remain and, during the past year, we have investigated a number of them.

The occurrence of direct channel resonances in πp scattering is an important feature of these collisions. At low energies, discrete resonances are observed. There has been considerable speculation about the role of resonances at higher energies. In particular, Frautschi has proposed that at high energies, a large number of resonances overlap and result in statistical fluctuations in the elastic cross-section. Argonne E-365 was designed to test these ideas. Data analysis during the past year has shown that both the π^+ and $\pi^- p$ cross-sections do show fluctuations, but that their amplitude and mass distribution are not consistent with Frautschi's model unless one makes unconventional assumptions about the ensemble of resonances (See Figure 1). The necessary assumptions would contradict the

Table 1. Currently active experiments of the high energy group.

Experiment No.	Short Title	Activity This Year	Current status
Argone E-305	Phi Production	Publication of results.	Published
E-365	Elastic Scattering	Analysis and publication of results	Some data published; analysis continues
E-393	Inelastic Asymmetries at 6 GeV/c	Analysis and publication of results	Published
E-407	Depolarization	Analysis	Analysis complete
E-408	Inelastic Asymmetries at 11.75 GeV/c	Publication of results	Published
E-411	Search for Psi Production	Publication of results	Published
E-414	p-^{4}He Elastic Scattering	Analysis and publication of results	Published
E-415	Direct Electron	Data collection and analysis	Analysis complete
E-418	pn Polarization	Data collection and analysis	Analysis continues
E-437	Low Energy Polarizations	Data collection and analysis	Analysis continues
Fermilab E-272	Coherent Production	Construction and installation	Beam starts in late 1977

exponential increase of resonance number density with mass that comes from statistical models of hadron interactions. The data taken at Argonne also disagree with earlier measurements at CERN, which claimed to show sharp changes in the large angle π^+p cross-section with a c.m. energy change that was a fraction of the π mass.

The data from E-365 have also been analyzed in another way. Parton model treatments of elastic scattering make predictions about the s dependence of 90^0 c.m. cross-sections. The sparcity of earlier data were not inconsistent with these predictions. In E-365, cross-sections were measured at intervals of 1 percent in incident momentum and 0.02 in $\cos\theta^*$ from 1.9 to 9.8 GeV/c for negative beam and 1.9 to 7.1 GeV/c for positive beam. With these fine steps in s, we found that the 90^0 πp cross section could not be well represented by a power law in s. Rather, it had a rich diffraction-like structure (see Figure 2), none of which had an exponent that agreed with the parton model prediction. The pp cross-section agreed better with the power law behavior, but still some structure was observable.

Our other studies of elastic scattering were particularly concerned with spin dependence. This is an important subject because only spin dependent measurements can reveal the entire amplitude structure of the elastic scattering process. During the past year, we have completed measurements of several reactions at incident momenta ranging from 1.2 to 6 GeV/c.

In Argonne E-393, we measured pp elastic polarizations at small t as a systematic check on the experimental apparatus. These data, however, proved to be the best existing measurements at small t and we have published them together with a phenomenological fit to all the world's data at this

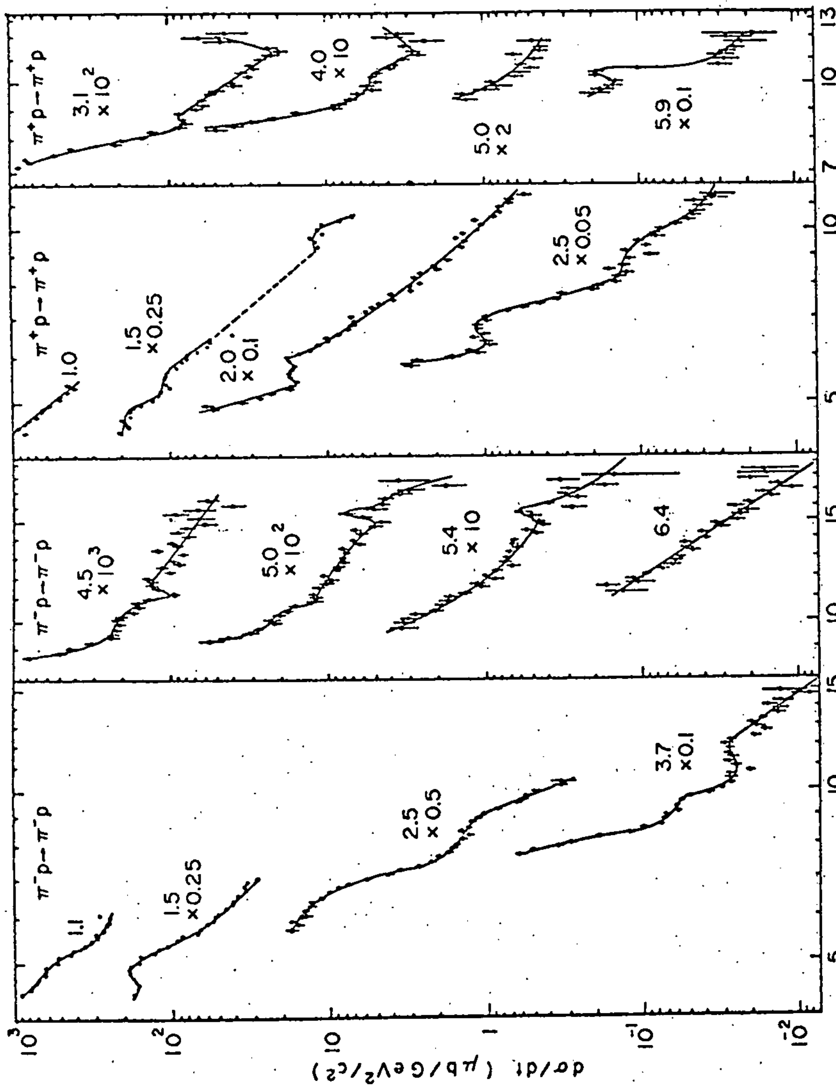

Fig. 1--Fluctuating cross-sections for πp scattering as a function of s.

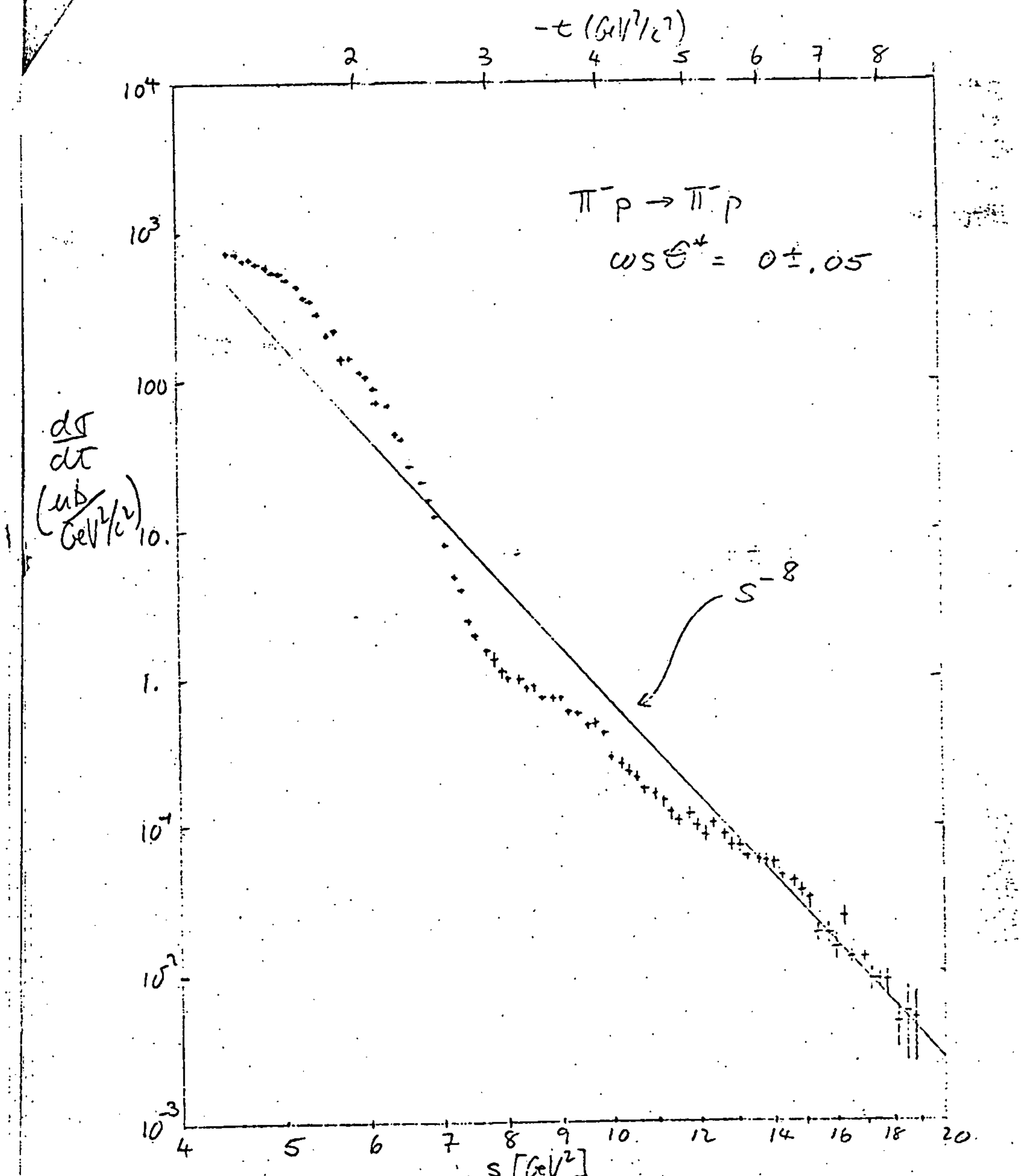

Fig. 2--s dependence of the 90° cross-section in πp scattering.

momentum. The fit elucidates the rise of the polarization away from the necessary zero in the forward direction.

The difficulty of detecting neutrons and of preparing a polarized deuteron target have resulted in a paucity of spin information about high energy pn scattering. Study of this reaction provides a useful compliment to the large amount of information known about spin effects in the isospin-related pp scattering process. Data taken previously in the forward and backward directions have shown that pn and pp polarizations are very different. In E-418 we have collected the first comprehensive large angle pn polarization data. Measurements were made at 2, 3 and 6 GeV/c incident momentum. Although analysis of the data is in process, preliminary results show that pn polarizations are considerably different from pp; they even become negative at large t (see Figure 3).

The problem of proton-nucleus interactions at incident kinetic energies near 1 GeV is interesting for several reasons. The data can be used both to test models of the scattering process from an extended object like the nucleus and to determine previously unknown information about the nucleon-nucleon (particularly pn) scattering amplitudes. Again, spin information is important for a detailed comparison between experiment and theory. We have, therefore, measured polarizations and cross-sections in p-^{4}He and p-d elastic scattering at energies between 0.56 and 1.7 GeV (see Figure 4 and Figure 5). In the case of the helium target, these unique polarization measurements have helped considerably to distinguish between possible parameterizations of both nuclear wave functions and nucleon-nucleon scattering behavior. The helium cross-section data have also proved useful in settling a factor of two discrepancy between measurements at other laboratories. The data from E-437 are still under analysis. However,

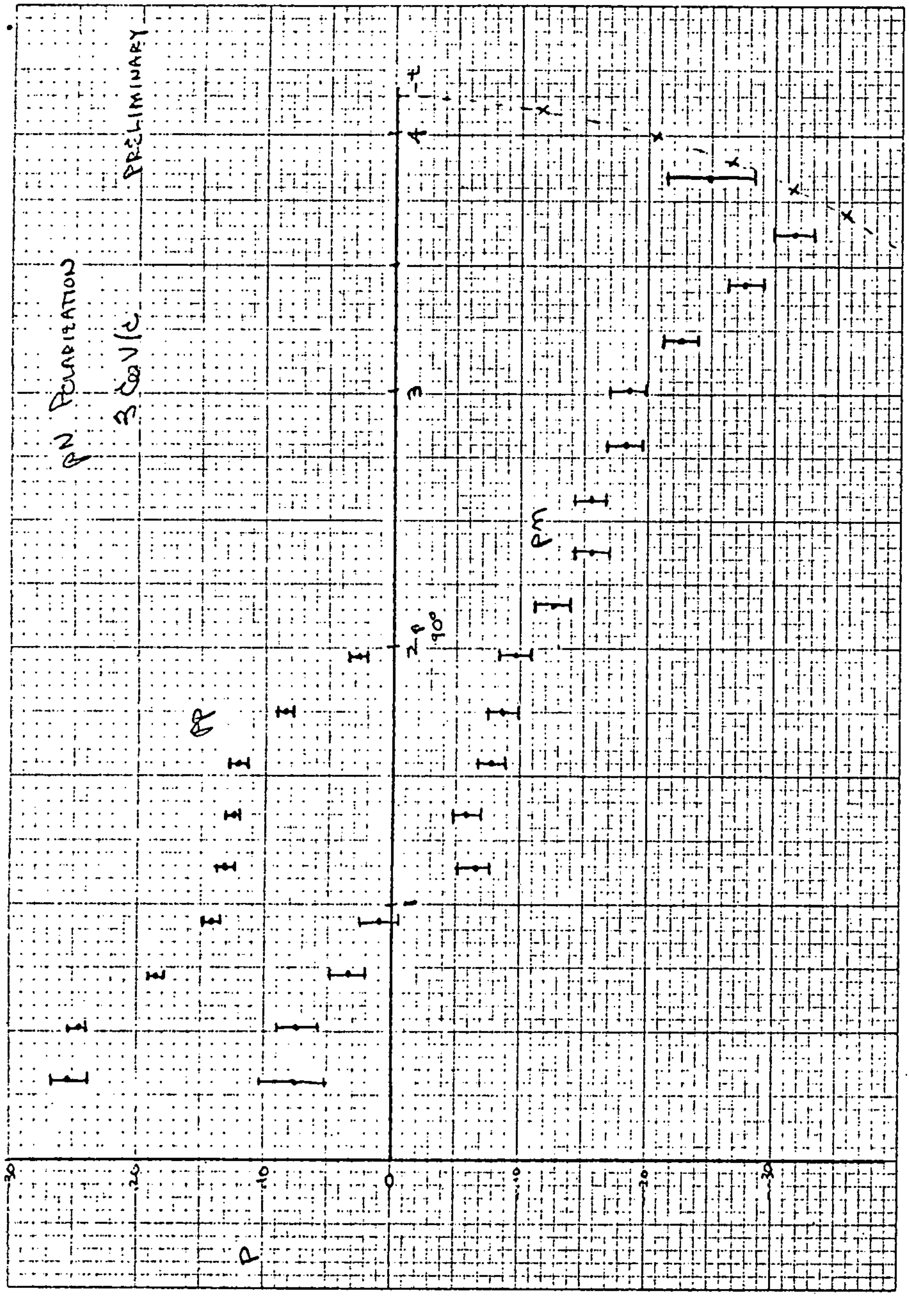

Fig. 3--pn polarizations at an incident momentum of 3 GeV/c.

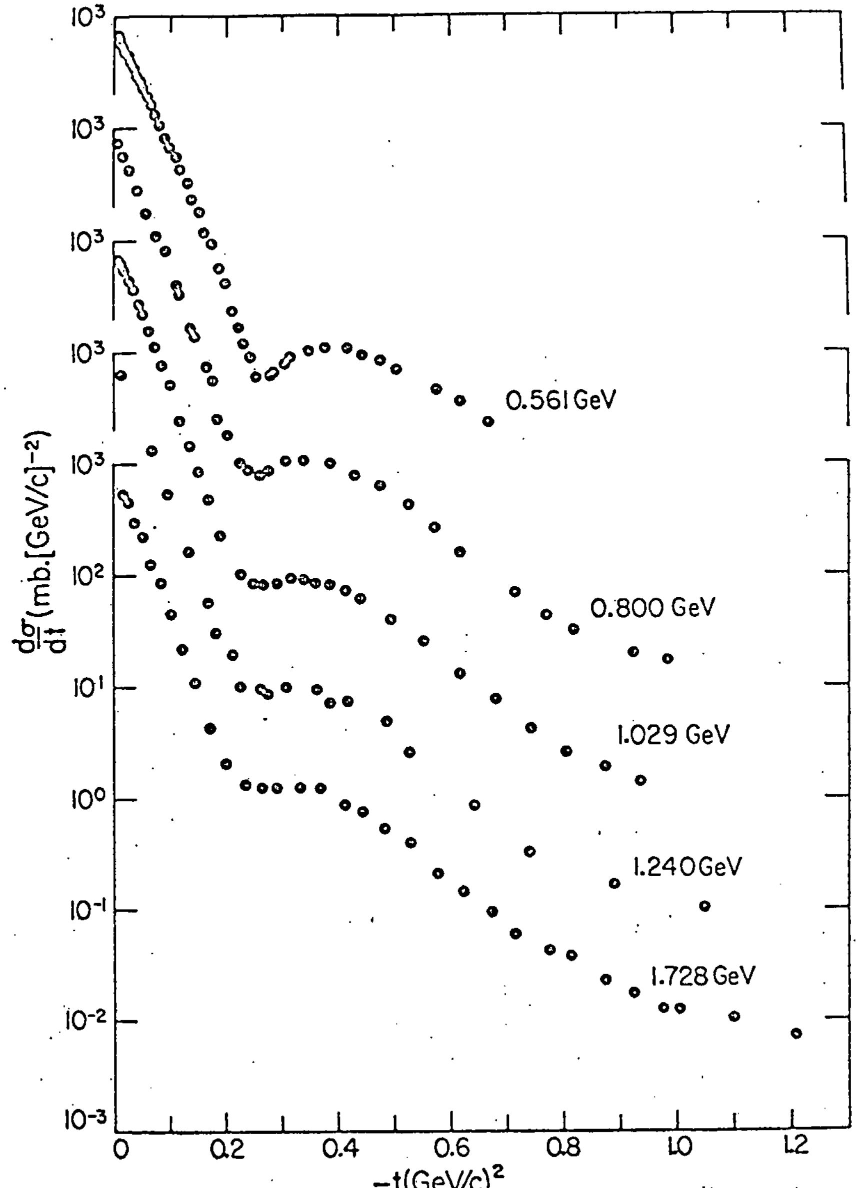

Fig. 4--Differential cross-sections for p-^{4}He elastic scattering.

preliminary results from the backward pd polarization measurements give support to the hypothesis that this process is dominated by a baryon exchange mechanism. In this experiment, we have also measured both pp and pn polarizations in order to compile a consistent set of data measured under identical conditions.

Particle Production Experiments

We have been active in three experiments during the past year which were designed to give information about known particle production mechanisms or to search for new mechanisms. In E-305, we were concerned with ϕ meson production in the region of the threshold enhancement. Cross-section, angular distribution and decay information were presented in the final report on this experiment. These distributions were all consistent with isotropy, which places limits on the mechanisms that can be used to explain the enhancement (see Figure 6).

The similarities between the ϕ and the ψ suggested to us the possibility of a similar enhancement near threshold in the cross-section for the process $\pi^- p \to \psi n$. E-411 was designed to detect this process with a sensitivity of order 1 nb. The results were consistent with no events, which indicates that either there is no enhancement or that it is smaller than expected from some models. We expect that both these measurements will provide strong constraints on models of the threshold enhancement process.

The question of the production of direct leptons in hadronic collisions has caused considerable controversy in the last few years. Such processes, if they exist, could indicate the presence of a heavy lepton or they could

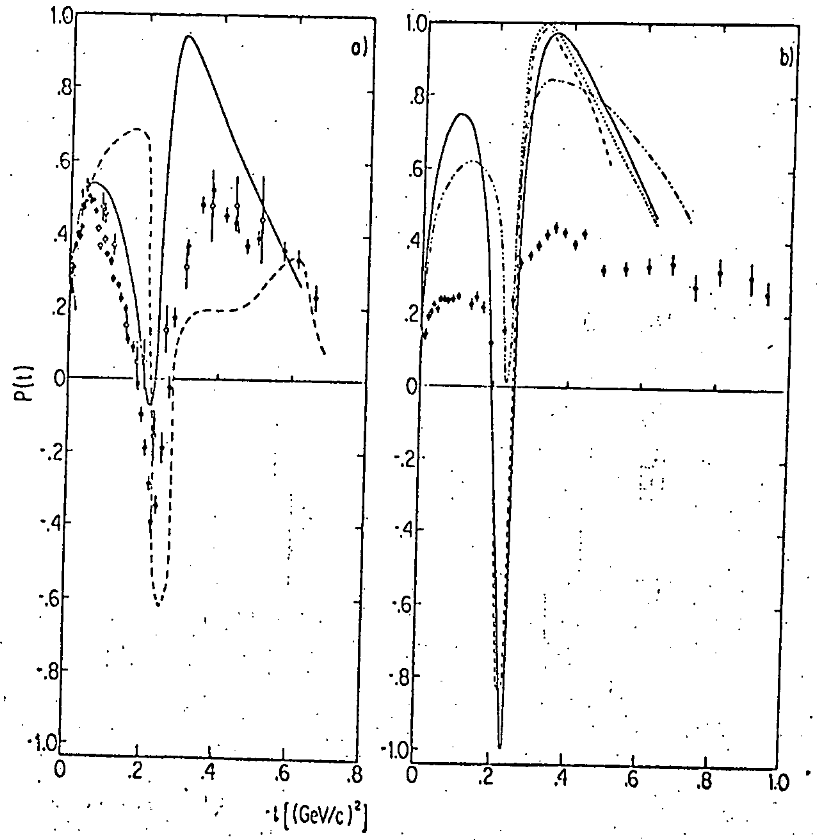

Fig. 5--p-^{4}He polarization data at incident kinetic energies of 0.56 and 0.80 GeV. Lines are theoretical predictions

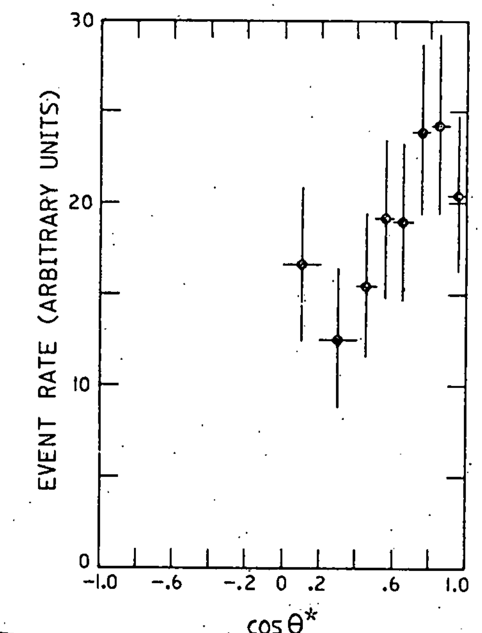

Fig. 6--Angular distribution for ϕ meson production in $\pi^{-}p$ collisions near threshold.

shed light on the nature of the lepton continuum in these reactions. A previous experiment showed direct electron production at the level of 10^{-4} for the ratio e/π at incident proton momenta of 10-25 GeV/c, with a marked rise at low momentum transfers. In E-415, we have studied direct electron production at 3, 6 and 12 GeV/c at lab angles of 3.5^0, 7^0, 13^0 and 20^0 from targets of hydrogen, deuterium, beryllium. Our results are consistent with no direct electron production other than that from vector meson decay (see Figure 7). We expect that other experiments will be done in this energy range but it seems that such searches should concentrate on the higher energy regime.

Spin Effects in Inelastic Scattering

In the past two years, we have performed a number of experiments studying the spin dependence of inelastic pp interactions. In the last Progress Report, we included our measurements of inclusive pion asymmetries, which appear to have a structure dominated by baryon exchange processes. The data from those experiments has now been completely analyzed and submitted for publication. This new analysis shows little structure in the K^+ and K^- asymmetries, even though they are as large as 40-50 percent. It also indicates that the isospin of the target has little effect on the inclusive asymmetries for meson production, but that the asymmetry for the process $pn \rightarrow p$ is considerably different from the asymmetry for the process $pp \rightarrow p$ (see Figure 8). This observation in the inelastic case seems a reflection of the difference already discussed for elastic scattering.

In E-407 we measured an additional spin parameter of inelastic pp

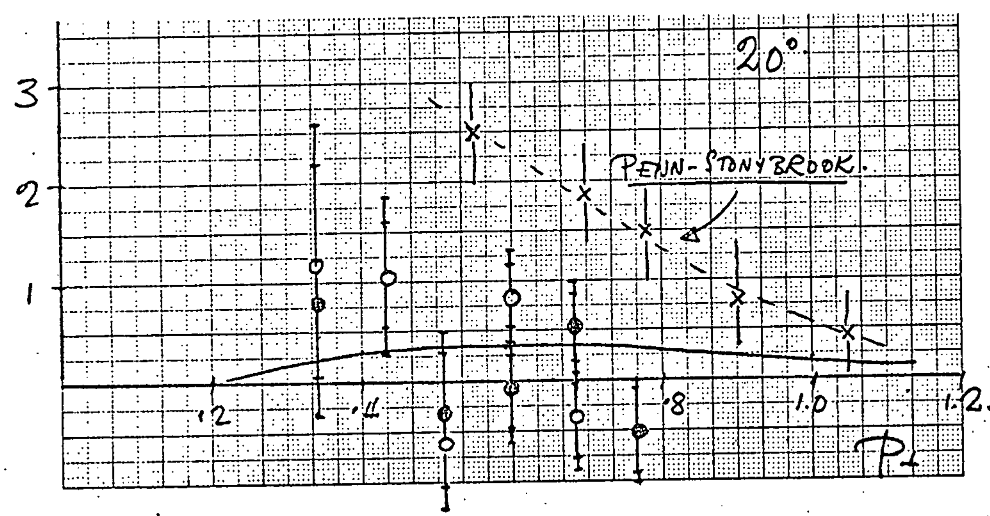

Fig. 7-- e/π ratios for direct electron production ($\times 10^4$) in pp collisions at an incident momentum of 12 GeV/c.

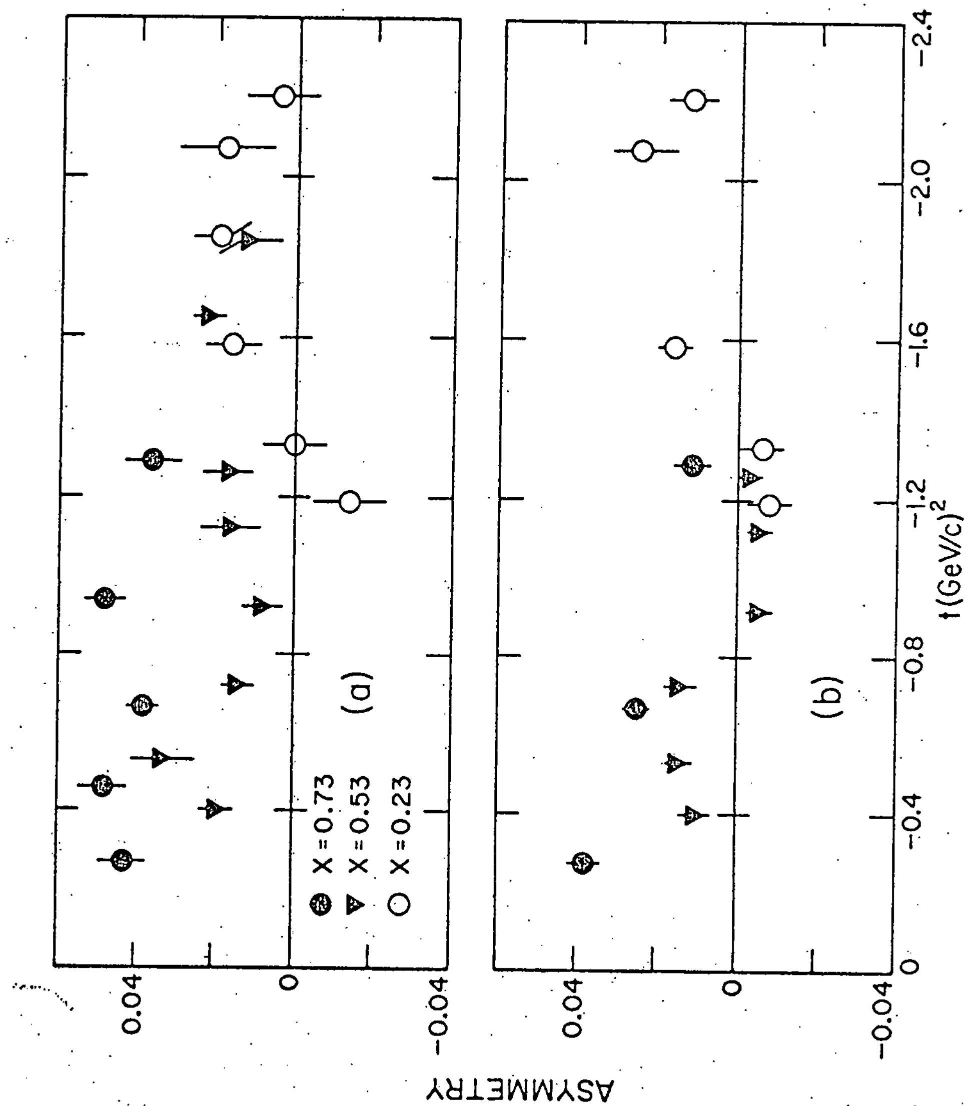

Fig. 8--The inclusive asymmetries for pp $\rightarrow$ p (a) and pd $\rightarrow$ p at an incident momentum of 11.75 GeV/c.

interactions, namely the depolarization parameter, which relates the spin of the outgoing proton to the spin of the incident proton. This parameter is simply related to the naturality of the exchange process. In particular, since elastic scattering is dominated by natural parity exchanges while the process $pp \rightarrow p\Delta$ has a considerable unnatural parity component, large structure in D should be observed as a function of missing mass. The analysis of this experiment is continuing, but preliminary results indicate that at some kinematic points D becomes negative for Δ production, which indicates strong unnatural parity contributions.

Coherent Production

As expected, Fermilab E-272 is now scheduled to receive first beam in the last part of 1977. During the past year, construction and installation of the experimental apparatus has continued. The current situation is that the liquid argon detector is assembled and is under test, the drift chambers have been constructed, the electronics for the chambers have been constructed and are under test, many of the scintillation counters have been constructed and installed and the drift chamber encoders have been purchased. Development of on-line and off-line analysis programs is in progress.

After testing and calibration of the detection apparatus, we will concentrate on measurements of the coherent Coulomb processes $\pi \rightarrow e$ and $K \rightarrow K^*$. These measurements will yield the absolute electromagnetic couplings of the vector mesons, which can then be compared with the predictions of symmetry models. This comparison is particularly important because, although these models have had numerous successes, their electromagnetic coupling predictions are in severe disagreement with the fragmentary data that exist on these processes.

Reprints Removed

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