Foreword

The University of Minnesota is perhaps unique in the wide range of programs supported under one U.S. E.R.D.A. basic research contract. Within a single task, this contract includes theoretical nuclear structure, theoretical high energy and experimental high energy research. In our view, this diversity is a source of strength. The history of physics teaches us the importance of recurring themes; concepts that are successful in one sub-field often have important applications in another. The close ties among the various researchers under this contract encourage this process of cross-fertilization. The results presented here stand as evidence of the advantages of this unique grouping.

This diversity, however, does create problems in writing a unified Progress Report for this contract. The sections dealing with theoretical programs, in particular, are anthologies of the contributions of different people. The exigencies of experimental research, on the other hand, demand close cooperation. Thus, the report of the experimental group is more unified. These different styles, which comprise this report, represent the way in which research is actually done. We hope that both the content and style of this report will prove illuminating.

Cover: The graph on the cover depicts the polarization in elastic p^4He scattering at an incident proton momentum of 1.2 GeV/c as a function of the momentum transfer in inverse fermis. This is preliminary data from Argonne ZGS E-414 taken during August, 1976. This experiment is discussed in the experimental high energy section of this report.

DISCLAIMER

Form-Factors for Two-Neutron Transfer Reactions

In the past decade, much effort has gone into using DWBA analyses of two-nucleon transfer reactions to test the predictions of shell-model calculations for target and residual nuclei. However, two-nucleon transfer reactions are generally dominated by the region of configuration space in which the two transferred neutrons are at the surface of the target nucleus, or a few Fermis beyond, whereas the shell-model wave functions give a poor description of the wave function in this peripheral region. A method has been developed to improve the peripheral part of the shell-model wave functions. This method is based on the traditional "separation-energy method", but takes account of the extra correlation between the trasferred nucleons due to their mutual interaction.

Finite-Range, Full-Recoil Calculation for One-nucleon

The code written last year was tested and perfected, and applied to the analysis of the data of Dehnhard and Petersen for the ($^{18}O,^{17}O$) stripping reaction on targets of ^{28}Si, ^{40}Ca, ^{48}Ca and ^{54}Fe. Comparisons with the data were done for the outgoing ^{17}O in its ground ($5/2^+$) state or first-excited ($1/2^+$) state. The spectroscopic factors extracted from this analysis were in good agreement with those extracted from previous neutron transfer studies using the (d,p) reaction. This provides a verification of the applicability of DWBA to ($^{18}O,^{17}O$) reactions on medium-weight targets.

Three-Nucleon Transfer Reactions (with Ali Evinay)

A zero-range DWBA code was written for the analysis of (p,α) and (α,p) reactions. The nucleons are picked from, or stripped into, shell-model states calculated with a Wood-Saxon potential. The use of these Wood-Saxon wave functions, rather than the simpler but less realistic harmonic-oscillator wave functions, is found tohave a significant effect on the predicted differential cross-sections.

Particle-Rotor Coupling Model (with R. Falkenberg)

A study has been made of the motion of a nucleon moving in the field of a deformed core, which is free to rotate. This is a generalization of the classic calculation by Nilsson for the motion of a nucleon in the field of a fixed deformed core. The ability of the core to recoil under the influence of the nucleon means that the Coriolis coupling not only mixes bands, but distorts them as well, in the sense that the "Nilsson" wave functions acquire a dependence upon the total angular momentum of the state. The model is also used to study the transition from strong to weak coupling.

Model of the Behavior of Solid Objects During Collision

When two hard solid objects collide, acoustic waves are generated at the point of impact. The deformation of the objects and their subsequent separation are associated with the propagation of these acoustic waves through the objects and their reflection from the surfaces. The time development of these processes is followed in detail for one-dimensional collision of Hooke's law springs. We calculate the degree of inelasticity of the collision from the state of internal excitation of the springs after separation occurs. The conclusions obtained in this one-dimensional model are generalized to yield a qualitative description of the collision of hard spheres. (American Journal of Physics 44 (1976) 671.)

Theory of Hitches

If one end of a rope is tied to a pole and the other end is pulled, the knot may slip or hold fast. A method is developed to predict which will happen. The topology of the knot determines an inequality involving the coefficients of friction characteristic of the rope and pole. If this inequality is satisfied, the different turns of the knot press on each other, and on the pole, to produce a self-locking unit that can withstand an arbitrarily strong pull. (To be published in the American Journal of Physics.)

Y. C. Tang

Study of Light-Ion Interaction with ^{16}O (with D. R. Thompson and M. LeMere)

The single-channel resonating-group method is used to study the interaction of light ions (n, p, d, t, ^3He and α) with the ^{16}O nucleus. The ^{16}O wave function used is a translationally invariant antisymmetrized product of single-particle functions of $(1s)^4(1p)^{12}$ configuration in a harmonic-oscillator well having an appropriately chosen width parameter. The wave functions for the light ions are assumed to have $(1s)^n$ configurations in harmonic-oscillator wells with width parameters chosen to yield the experimentally determined rms radii. The nonlocal interactions between the clusters are computed with a recently developed generator-coordinate technique (Phys. Rev. C12, 1432 (1975)), generalized to the case where the clusters involved are described by wave functions of unequal width parameters.

From this investigation we gained information concerning the structure of rotational bands in the compound nuclei involved. For instance, in the nucleus ^{20}Ne it was found that there exist not only a ground $K^\pi = 0^+$ band consisting of levels with ℓ having even integral values from 0 to 8, but also a $K^\pi = 0^-$ band and an excited $K^\pi = 0^+$ band. In fact, there is even an indication for the existence of an excited $K^\pi = 0^-$ band. The states in this latter band are, however, quite broad and, consequently, their presence will be hard to verify experimentally.

By further introducing phenomenological imaginary potentials into the resonating-group formulation to take approximate account of reaction effects, we have also made comparisons between calculated and experimental differential cross sections and polarizations at energies where reaction channels are open. These comparisons yielded quite satisfactory conclusions, thus indicating that the resonating-group method, together with the generator-coordinate technique, can be successfully used to study even nuclear systems which involve a rather large number of nucleons.

Resonating-Group Study of the N + ^{40}Ca System (with D. R. Thompson and M. LeMere)

The N + ^{40}Ca system is studied with the resonating-group method. The ^{40}Ca wave function used is a translationally invariant antisymmetrized product of single-particle wave functions of $(1s)^4(1p)^{12}(2s)^4(1d)^{20}$ configuration in a harmonic-oscillator well having an appropriately chosen width parameter. A generator-coordinate technique is employed to compute the non-local interaction between the nucleon and the ^{40}Ca nucleus.

The results of our calculation have been compared with experimental data on bound states in ^{41}Ca, as well as n + ^{40}Ca and p + ^{40}Ca differential cross-section and polarization data at various energies. In each of these comparisons, it was found that our results are generally quite satisfactory. In fact, the fits to experimental data on cross sections and polarizations are of the same quality as those obtained by conventional optical-model analyses where many adjustable parameters are employed.

Together with our previous studies of N + α and N + ^{16}O systems, we have also learned the importance of antisymmetrization effects in nucleon-nucleus scattering. It was found that the knockout exchange term does not, in general, become less significant as the target mass increases. On the other hand, the heavy-particle pickup exchange term does seem to become less important with increasing target mass. It is mainly this latter feature which enables the optical model to yield a reasonable description of nucleon scattering on medium- and heavy-weight nuclei.

Influence of the Pauli Principle on the Optical Potential for α + ^{16}O Scattering (with D. R. Thompson, R. A. Partridge and R. E. Brown)

The scattering of α particles by ^{16}O is studied with a simple model which employs an effective intercluster potential containing both a Pauli repulsive core and an odd-even dependence on the orbital angular momentum. The result shows that this model can reproduce all the essential features of this problem, including that of large back-angle enhancement in the differential cross section.

P. J. Ellis

Effective Operators in the Shell Model

Work should be completed in the next few weeks on a "tutorial-style" article on effective operators for Reviews of Modern Physics aimed at the graduate student and non-specialist. We discuss the time-independent formalism of Brandow for effective operators in a non-rigorous, intuitive way using the simple example of a 2 x 2 matrix to introduce the notion of folded diagrams, the factorization theorem, etc. The same example is used in discussing the formal properties of the effective interactions. A fairly comprehensive summary of the numerical calculations to date is given using simple physical models for illustrative purposes whenever possible. We attempt to synthesize the results and draw conclusions. (with E. Osnes, Stony Brook and Oslo).

We have completed a simple model study of Hartree-Fock effects for the effective integration in ^{18}O. The model involves taking harmonic oscillator wave functions with parameter b = 1.7 fm for the 0s and 0p orbitals and variable parameter b_u for the unoccupied (sd) and (pf) orbitals. A central interaction was used and diagrams of first, second and third order were calculated. The model is found to reproduce the qualitative features of first and second order calculations. The dominant trend of the results is an exponential fall off in the magnitude of the diagrams as b_u increases. Comparing b_u of 2.0 fm and 1.7 fm (roughly Hartree-Fock versus pure oscillator).

we obtain reductions of about 0.7, 0.7^2 and 0.7^3 in first, second and third order respectively. It is found that diagrams containing a particle-particle ladder fall off less slowly than the others which can be important in reducing vertex correction effects to the core polarization diagram. This will be submitted for publication shortly (with F. L. Goodin (Minnesota graduate student) and P. Goode (Rutgers)).

A code was written to obtain linked effective interactions from matrices containing $0 + 2\hbar\omega$ excitations according to the technique of publication COO-1764-217. Calculations are being carried out for the A = 4-6 nuclei. At the moment results have only been obtained for 1 hole $2\hbar\omega$ states and we observe that the unlinked diagrams shift the diagonal (j-j coupled) elements of the effective interaction by about 200 keV. This is comparable to the results of Kirson and Starkand (Phys. Lett. <u>55B</u>, 125 (1975)). The effect of 2 hole $2\hbar\omega$ states has never been tested and we anticipate much larger effects when they are included (with P. Goode - Rutgers).

We have extended the second order results of Ellis and Siegel (Phys. Lett. <u>34B</u>, 177 (1971)) to include folded diagrams to higher order as an illustration of the $\hat{Q}$-, $\hat{X}$- and divided $\hat{Q}$-box technique of Krenciglowa and Kuo (Nucl. Phys. <u>A240</u>, 195 (1975)). Some subtleties in the approach are discussed and the folded diagrams are found to reduce the non-folded values of the effective charge by 5-15%. Submitted for publication; a short report was previously contributed to the Tucson Conference (1975) (with E. M. Krenciglowa, T. T. S. Kuo and E. Osnes, Oslo and StonyBrook).

The Quadrupole Moment of the 2_1^+ state of ^{18}O

According to the weak coupling (and all other) shell model calculations the wave function of the 1.98 MeV 2_1^+ state of ^{18}O is dominantly $(sd)^2$ with small $(sd)^4\ p^{-2}$ components. The quadrupole moment of each of these pure configurations is -2.7 and -15 efm^2 respectively. Weighting these values with the appropriate intensities yields a calculated $Q(2_1^+) = -\ 3.4$ efm^2 which rises to -4.8 efm^2 if the effective charge is scaled to give the experimental $B(E2\ 2_1^+ \rightarrow 0_1^+)$. The recently measured value is -19 ± 2 efm^2 (Kleinfeld et.al. Phys. Rev. Lett. 35, 1329 (1975)) which would suggest a pure $(sd)^4p^{-2}$ configuration. On the other hand for the magnetic moment of the 2_1^+ level pure $(sd)^2$, pure $(sd)^4p^{-2}$ and mixed weak coupling wave functions yield -0.73, + 1.0 and -0.61 μ_N respectively. The latter is in good agreement with the measured value of -0.70 ± 0.08 μ_N (Speidel et.al., Phys. Lett. 57B, 143 (1975)) which seems to rule out large $(sd)^4p^{-2}$ components. A remeasurement of the quadrupole moment was urged (preliminary results of Minnesota and Rochester work are unfortunately in agreement with the Kleinfeld value). Published in Phys. Rev. Lett. (with T. Engeland, Oslo).

The $^{16}O\ (d,{}^3He)^{15}N$ Reaction in Coupled Channel Born Approximation (with A. Dudek-Ellis)

The study of the $^{16}O(d,{}^3He)^{15}N$ reaction, mentioned in previous reports, has finally been completed. The main feature here was that a CCBA calculation was necessary to account for the cross sections of the $5/2^+$ and $7/2^+$ levels. Thus it is not possible to use the DWBA to estimate the amount of closed shell breaking. Published in Nuclear Physics (with M. A. Firestone and J. Jänecke, Michigan and T. Engeland, Oslo)

^{3}He Inelastic Scattering on ^{24}Mg and ^{28}Si (with A. Dudek-Ellis)

The study of ^{3}He inelastically scattering to the lowest 2^{+} and 4^{+} levels of ^{24}Mg and ^{28}Si using both macroscopic and microscopic form factors in coupled channels calculations is close to completion. In the microscopic case we use simple configurations, a renormalized nucleon-nucleon interaction for $L \neq 0$ form factors and the optical model for $L = 0$. It was, of course, necessary to enhance the $L = 2$ matrix elements so as to reproduce the observed B(E2) (reorientation processes were found to be very small); as regards $L = 4$ the calculation was only sensitive to the 0^{+}-4^{+} matrix element and here no enhancement was required. In this way a fairly reasonable account of the data could be achieved, although it should be noted that the shape of the ^{28}Si 4^{+} cross section was poorly given. The macroscopic model also experiences difficulty here and we await completion of the macroscopic study by our coworkers (with D. Dehnhard and H. P. Morsch, Minnesota).

Indirect Excitation of Low-Lying 0^{+} States

Using simple macroscopic form factors we studied the indirect excitation of low lying 0^{+} states by inelastic scattering through the lowest 2^{+} states for the reactions ^{24}Mg(α,α'), ^{28}Si(α,α') and ^{46}Ti(^{3}He,^{3}He'). Scaling amplitudes according to the inelastic scattering and B(E2) data we found that only for α scattering from ^{24}Mg was indirect excitation small. For the other cases studied our estimate yields indirect cross sections which were significant in comparison to the data, although this has been well described by the direct one-step process alone. The shape of the indirect cross section may be either strongly oscillatory or flat, depending on the radius of the real optical potential. To be published in Physics Letters. (with H. P. Morsch, Minnesota and Michigan State).

Multi-Step Processes in Heavy Ion Stripping Reactions (with B. F. Bayman and A. Dudek-Ellis)

In order to study multi-step processes in heavy ion stripping reactions by combining the coupled channel Born approximation (CCBA) and finite range full-recoil form factor codes available at Minnesota a number of developments were necessary. Firstly, the one-nucleon form factor code needed to be put into a form suitable to receive the entrance CC results and generate the source term. Also in the process of checking the code against DWBA results generated with LOLA some differences in the predictions were uncovered— these have now been resolved. Secondly some modifications of the CC code INCH were necessary to accomodate heavy ions. The Coulomb function and basic CC integration subroutines required changes. In particular for the latter the more accurate integration method labelled Cowell-Crommelin or modified Numerov is now used. Finally, several modifications were investigated to speed up the code since Coulomb excitation implies many partial waves and integration to large radii. We are now in a position where we can carry out useful calculations.

S. F. Tsai

Coordinate-space HF-RPA

A coordinate space formalism was used by Blomqvist (Phys. Letters 28 (1968)22) to generalize the RPA (Random-phase-approximation) schematic model. This approach was possible with zero-range forces. It allows fast computation even in heavy nuclei while enabling all one-particle-one-hole excitations to be included.

This formalism is rederived using Green's function technique based on the RPA eigenvalue equation in particle-hole representation commonly used in nuclear problems. Its applicability is further extended to include energy-independent local interactions. A study of the spin-dependence in the Skyrme interactions, which was proposed previously, thus turned out to be unnecessary, as together with Hartree-Fock (H-F) calculations, this approach provides one of the best tests on how realistic an interaction is. A possible candidate currently under study is the local-density-approximation effective interaction.

Nuclear G-matrix

With an (E-QTQ) type energy denominator in the propagator of the nuclear Bethe-Goldstone equation, Znojil's recent exact solution (Phys. Rev. C12 (1975) 2077) for the defect wave function is shown to follow from Tsai and Kuo's earlier exact solution (Phys. Letters 39B (1972) for the G-matrix.

S. Gasiorowicz

Studies in Quark Confinement Models

I continued my studies of a class of models invented by Kogut and Susskind which show electrical flux confinement through a field-dependent dielectric constant. My analysis of this model (Physical Review D12, 2526 (1975)) showed that classical solutions to this nonlinear problem come in discrete steps, so that even classically the flux is quantized. I investigated the question whether such discrete solutions, accompanied by quantum fluctuations, could in any way mimic the existence of classes of heavier and heavier quark theories. Unfortunately, this does not seem to be the casesince there is no mechanism by which transitions from one "band" of solutions to another one are suppressed, so that one cannot associate conserved quantum numbers with the bands.

Calculations indicate that nonlinear quantum effects are important, so that expansion about classical solutions is a questionable procedure (particularly so in view of recent results involving the so-called "instantons"). The only new nonperturbative approach that is purely quantum-mechanical is the lattice quantization method introduced by Wilson. I have generalized the Hamiltonian method of Kogut and Susskind to SU(3), and the generalization to SU(N) is being carried out, to see whether the large N limit singles out some classes of states in the Wigner-Brillouin perturbation expansion. The extension to a group larger than SU(2) complicates the fermion problem, and I have not been able to invent a method for treating them in a way that manifestly breaks the chiral invariance of the underlying theory. Work is continuing on this problem.

Recently, Migdal has written a paper purporting to derive meson Regge trajectories from quantum chromodynamics. At the Aspen workshop on Elementary Physics, P. Kaus of U. C. Riverside and I undertook an examination of the paper. We found some difficulties with the paper in that (a) the trajectory condition persists in the weak coupling limit, and (b) it appears to be possible to derive the trajectory condition for theories that are not asymptotically free. Nevertheless the question of how to formulate confinement generally for propagators of composite operators is interesting and the collaboration is continuing.

Donald A. Geffen

An Energy Dependent Chou-Yang Model With the Y-Graph Correction (with D. D. Coon, University of Pittsburgh and J. Tran Thanh Van, University of Paris-Sud, Orsay, France)

We have completed our phenomenological analysis of high energy proton proton elastic scattering, using the eikonal representation for the scattering amplitude. We have been able to describe the energy dependence of the elastic scattering cross section, $d\sigma/dt$ by extending the Chou-Yang model to include a significant correction due to the contribution to the elastic amplitude that arises from the iteration of inelastic diffractive processes. While more data and additional analyses are necessary, we believe that our results are sufficiently definitive to conclude that this is the most promising approach to understanding diffractive processes.

By using the MINUIT minimization program on the UNIVAC 1110 at Orsay, we were able to explore a range of possible models and reach the following conclusions.

1. The opacity is predominantly given by a Chou-Yang term proportional to the square of the hadronic matter distribution form factor for the proton, F(t), multiplied by an energy dependent factor which increases by a few percent as p_L increases from 500 to 1500 GeV. We found no evidence to indicate the presence of shrinkage in the opacity. If such shrinkage were present, it could be at most a small fraction of the observed shrinkage in the forward diffraction peak.

2. The Y-graph correction, as we call the term arising from inelastic diffraction, is found to be important for only small momentum transfer, i.e. $| t | < .4(\text{GeV})^2$. It's magnitude is of the order of magnitude expected from measured inelastic diffraction crosssections.

3. The sign of the Y-graph term <u>required</u> to fit the data is strongly correlated with the rate of fall with increasing $| t |$ of $F(t)$, the hadronic matter distribution in the proton. A positive Y-graph contribution (arising when inelastic diffractive amplitudes are predominantly real) requires an $F(t)$ which behaves like $F_1(t)$, the Dirac form factor. The Reggeon calculus predicts imaginary diffractive amplitudes and hence a negative Y-graph. We found that the <u>data favors this sign</u> for Y and requires an $F(t)$ falling more rapidly with increasing $| t |$ than $F_1(t)$, such as $G_{M_p}(t)$. Consequently, $d\sigma/dt$ which has always been sensitive to the shape of $F(t)$, becomes even more so when the Y-graph correction is included, provided its sign can be fixed.

4. Elastic electron-proton scattering experiments have only been able to measure separately G_{E_p} and $G_{M_p}(t)$ for values of $| t |$ restricted to $|t| < 2(\text{GeV})^2$. In this t range, $F(t)$ resembles most closely $G_{M_p}(t)/\mu_p$ or G_{M_n}/μ_n which has an almost identical t dependence over this range of t. $G_{M_p}(t)$ and $G_{E_p}(t)$ are not separately determined for $| t | \geq 2(\text{GeV})^2$. We think it likely from our results that $F(t)$ differs from the values of "$G_{M_p}(t)/\mu_p$" for $| t | > 1.75\ (\text{GeV})^2$ obtained from experiment under the assumption that $G_{M_p}/\mu_p = G_{E_p}$. Consequently, we conclude that the structure of $F(t)$ is still to be determined and is most uncertain as $| t |$ increases beyond $1\ (\text{GeV})^2$.

Several practical applications of the model come to mind. The fit to the forward diffraction peak, including shrinkage and curvature, is excellent and provides a reliable means of extrapolation of the data to $t = 0$ or across gaps at finite values of t. This reduces the uncertainty in the normalization of the data.

The observed energy dependence of $d\sigma/dt$ in the neighborhood of the diffraction dip provides clear evidence of interference between the diffractive and Regge exchange parts of the scattering amplitude. Our modified Chou-Yang model can provide a useful tool for learning about the properties of Regge exchanges at high energies.

Finally, our results provide additional support to the notion that hadronic interactions at high energies are dominated by the hadronic matter distributions which, with increasing likelihood, appear to be the distribution of quarks themselves. Future analyses of elastic and inelastic diffractive differential cross sections can yield insights into the quark (or parton)-like nature of hadrons. At present, however, we find one difficulty. Recent ISR measurements of $d\sigma/dt$ (p_L = 2000 and 280 GeV), including the absolute normalization, do not appear to be consistent with earlier unnormalized measurements at p_L = 200, 500, 1000, and 1500 GeV. Hopefully, this is an experimental problem. The modified Chou-Yang model is consistent with either sets of data taken separately but cannot describe, for example, the measurements at p_L = 1500 and 2000 GeV together. Further analysis, however, must await the resolution of this conflict.

The manuscript describing our work is now almost completed and we expect to submit it for publication within the next few months.

H. Suura

Locally Gauge Invariant Bilocal Operator and Quark Confinement

We have succeeded in constructing a locally gauge invariant quark-antiquark bilocal operator and using it to derive a relativistic c-number equation for a q-$\bar{q}$ system with a confinement potential. In QED it is known that

$$e^{-ie \int_c A_\mu(x) \cdot dx^\mu} \qquad \psi(1) \ \psi^+(2) \tag{1}$$

is a gauge invariant operator, where c denotes a path connecting points 1 and 2. In general (1) is a function of the end points 1 and 2, as well as of the path c. Since we want to use the bilocal operator to define a two-body c-number wave function, we would like to define a gauge invariant operator independent of the path. For this purpose, and also for extension to QCD, we make the following modifications to (1). 1. We take the 'spatial gauge' $A_0 = 0$. This limits the path in (1) to spatial paths connecting 1 and 2 for which we introduce a parametric representation $\vec{x} = \vec{x}(s)$ ($s = [0,1]$) with $\vec{x}_1 = \vec{x}(0)$ and $\vec{x}_2 = \vec{x}(1)$. The two points 1 and 2 must necessarily have equal times. The spatial gauge permits the canonical quantization of the non-abelian fields which is an additional advantage. We still have a limited gauge transformation $\vec{A} \to \vec{A} + \vec{\nabla} \vec{\Lambda}$ for which (1) is invariant. 2. To obtain path-independence, we average (1) over all possible $\{ c \}$

$$< e^{+ie \int_c \vec{A}(x) \cdot d\vec{x}} >_c$$

$$= \lim_{\lambda \to 0} \int d[x(s)] \quad e^{\int_c [-\lambda \dot{x}^2 + ie \vec{A} \cdot \dot{\vec{x}}] ds} \tag{2}$$

where $\dot{x} = d\, x(s)/ds$. The path-integral in (2) is defined exactly as in the original Feynman's definition. 3. Extension to the color gauge field A^a (a = 1, ..., 8) is done by replacing (1) by

$$L(1,2) = \mathrm{Tr} \quad [< P \quad e^{ig \int_c \frac{\lambda^a}{2} \vec{A}^a \cdot d\vec{x}} >_c \psi(1)\, \psi^+(2)] \tag{3}$$

where P denotes the 'path-ordered' product and the trace is on the color indices. Thus, L(1,2) is the gauge invariant, color-singlet and path-independent bilocal operator with equal times $t_1 = t_2$. Defining an equal-time c-number amplitude $\chi(1,2) = (\Psi_0 \ , L(1,2)\ \Psi \ )$, the wave equation is given by $W \chi(1,2) = (\Psi_0, [L(1,2),H]\Psi)$, where H is the field theoretical Hamiltonian for QCD. We obtain

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

$$= [W - V(1,2)] \ \chi(1,2) \tag{4}$$

where the potential V(1,2) is essentially the electric field energy (it comes from the commutator of L(1,2) with $\frac{1}{2}\int \vec{E}^a(x)^2 \, d^3x$) and is given by $V(1,2) = g_r(x_1 - x_2)^2$. Thus, we have obtained a relativistic confinement equation without using the lattice quantization.

In deriving (4) we have neglected a term, the validity of which must be further investigated. The equation (4) leads to the Klein paradox, which will be discussed in a separate report. The important feature of equation (4) is that the potential V(1,2) is essentially of electrostatic origin, and is a direct generalization of the Dirac Equation for the hydrogen atom.

A Relativistic Equation With A Confining Potential

As a relativistic equation for a q-$\bar{q}$ system bound by a potential $V(r)$, we investigated the equation

$$[- i \alpha \cdot \nabla + \beta m, \chi(r)] = [M-V(r)] \chi(r) . \qquad (1)$$

Here $\chi(r)$ is a 4 x 4 matrix and the commutator is between the Dirac matrices and $\chi(r)$. M is the mass of the system (eigenvalue) and m is the quark mass. We derived equation (1) field-theoretically (see above report), but quite generally it can be regarded as a straight forward generalization of the Dirac equation for the hydrogen atom, with $V(r)$ representing the 'electrostatic' potential. With a confining potential $V(r)$ rising indefinitely with r the equation has only run-away solutions because of the Klein paradox. Nevertheless, we propose to extract a meaningful eigenvalue problem from (1). In terms of the two sets of Pauli matrices $\{\rho_i\}$ and $\{\sigma_i\}$ with $\alpha = \rho_1\sigma$ and $\beta = \rho_3$, we can write $\chi = \sum_i \rho_i \chi_i + \chi_4$.
For the pseudoscalar singlet states which we examine as an example, we can find a solution of the form $\chi_i = Y_{\ell m} F_i(r)$ $(i = 1, 2)$ and $\chi_4 = 0$. Eliminating χ_3 and χ_1, we obtain

$$\frac{d^2F_2}{dr^2} + \left(\frac{2}{r} + \frac{V'}{M-V} \right) \frac{dF_2}{dr} + \left[\frac{1}{4} (M-V)^2 - m^2 - \frac{\ell(\ell+1)}{r^3} \right] F_2(r) = 0 \qquad (2)$$

If $V(r) \to \infty$ as $r \to \infty$, then for large r the term $+ \frac{1}{4} V^2$ dominates and we have only run-away solutions (Klein paradox). However, at the same time, we have a new singularity at r_0 ($M = V(r_0)$), where we have an infinite barrier. For $r \gg r_0$, where the Klein paradox occurs, two-particle description of the system fails. Our basic assumption is that the equation (2) is valid up to and including the singular point r_0. The boundary conditions imposed on F_2 at $r = 0$ and r_0 are independent of whatever modification we may make in the Klein paradox region, thus giving us an unambiguous eigenvalue problem. The regular solution at $r = r_0$ behaves like $(r - r_0)^2$ while the mildly singular solution at $r = r_0$ behaves like a constant. The latter must be excluded because $\chi_1 = - \frac{2im}{M-V} \chi_2$ would be singular there, making it impossible to normalize the wave function. Thus, the boundary conditions are

$$F_2(0) = \text{const.}$$

$$F_2(r_0) = F_2'(r_0) = 0$$

The latter boundary condition allows us to connect F_2 to $r \gg r_0$ where we can take $F_2(r) = 0$. In this way, we can investigate the relativistic kinematical effects of the electric quark binding.

Jonathan L. Rosner

Radiative decays $\psi' \to X\gamma \to \psi\gamma\gamma$ (with G. Karl and S. Meshkov)

Work was completed on an analysis of the information that can be extracted from angular distributions of photons and final leptons in $e^+e^- \to \psi' \to \chi\gamma \to \psi\gamma\gamma \to \ell^+\ell^-\gamma\gamma$.[1] This work has since been used at SPEAR to rule out J = 0 for the 3.5 GeV level; preliminary results[2] slightly favor J = 1 but are also consistent with J = 2.

Remarks on the new particles[3]

These were prepared for the 1975 meeting of the Division of Particles and Fields, American Physical Society. These observations served as a guideline for the author's continued interest in charmed particles during the year. They contained a prediction that the two-body decays of charmed particles (such as $D^0 \to K^-\pi^+$) would be observed at the few percent level, a result which has since been borne out by experiment.[4]

Hadronic experiments with hyperon beams (with C. Quigg)

The author was invited to speak on this topic at a workshop at Fermilab in December, and a collaboration was initiated to study the widest variety of possible hadronic experiments with hyperon beams. These included the study of total, elastic and inelastic cross-sections, the search for missing hyperon resonances, and the production of unusual charmed baryons.[5]

One-photon and two-photon radiative decays of mesons (with J. Babcock)

This topic, explored earlier for the new heavy mesons,[6] was dealt with for the lowest-lying negative- and positive-parity mesons.[7] The new relations, as yet untested, involve the combination of vector dominance with the single-quark-transition language of the Melosh transformation.[8] Interesting results which should be testable in the near future include a strong signal in $e^+e^- \to e^+e^-f_0$ via the two-photon process,[9] a branching ratio of about a percent for $f_0 \to \gamma\rho$, and the dominance of $\lambda = \pm 2$ in $f_0 \to \gamma\gamma$.

Implication of new set of resonance photocouplings (with J. Babcock)

The baryon resonance photocouplings of Barbour and Crawford[10] were subjected to the analysis developed previously for other sets of photocouplings.[11] It was found that if these photocouplings were assigned error bars from a previous analysis,[12] the new photocouplings gave a more satisfactory fit to the Melosh transformation description than those of Ref. 12, and definitely favored a particular relative phase of F-wave and P-wave πN couplings in the <u>56</u>, L = 2 multiplet.[13] This relative phase is such as to <u>disagree</u> with that derived from analyses of $\pi N \to \pi\Delta$.[14] It will be interesting to see if this contradiction persists in future sets of photocouplings; in that case a re-examination of the $\pi N \to \pi\Delta$ phases[15] may be in order.

Tests for weak decays of charmed particle candidates (with B. W. Lee and C. Quigg)

Some simple tests were noted for determining whether the new mesons at 1.87 GeV/c^2 [4,16] are in fact, decaying weakly.[17] If the Dalitz-plot distribution for $D^+ \rightarrow K^-\pi^+\pi^+$ does not vanish on the boundary, and if it belongs to the same isomultiplet as the particle decaying to $K^-\pi^+$, then parity must have been violated in the decay. Other tests involve semileptonic and Cabibbo-suppressed decays.

Charmed Baryon interpretation of $\bar{\Lambda}\pi^-\pi^-\pi^+$ and $\bar{\Lambda}\pi^-\pi^-\pi^+\pi^\pm$ peaks (with B. W. Lee and C. Quigg)

The antiparticle of the charmed baryon (called C_0^+ in Ref. 18) seems to have been produced in a photon beam at Fermilab.[19] Its mass is 2260 GeV, very close to that of a single $\Lambda\pi^+\pi^+\pi^-$ combination seen earlier in a neutrino-induced event[20] and close to the prediction of Ref. 21. The charge state of the $\Lambda 3\pi$ peak (Q = -) also is consistent with its being the antiparticle of the charmed isosinglet baryon C_0^+. Further consequences of the charm hypothesis for the peak are explored. Isospin relations and predictions for the mean multiplicity of nonleptonic decay products are given and the $\bar{\Lambda}4\pi$ effect is predicted to have a two-peak structure whose detailed shape is predicted.

Isospin bounds on charmed particle decays (with M. Peshkin)

The fact that the charm-changing, strangeness-changing part of the weak Hamiltonian has $I = I_3 = 1$ implies definite relations among various final states, for example,

$$A(D^0 \to K^-\pi^+) + \sqrt{2}\, A(D^0 \to \bar{K}^0\pi^0)$$
$$= A(D^+ \to \bar{K}^0\pi^+) \quad , \qquad (1)$$

and

$$\frac{1}{2} \leq \frac{\Gamma(C_0^+ \to \pi^+\pi^+\pi^-)}{(C_0^+ \to \Lambda 3\pi)} \leq \frac{4}{5} \quad . \qquad (2)$$

A systematic study of such relations and bounds was begun during the author's stay at the Aspen Center for Physics. This work is continuing and results will be submitted for publication.[22]

Tests for CP violation in charmed particle decays (with M. Goldhaber and P. Sikivie)

The reactions ($e^+e^- \to D^0\bar{D}^0$ + neutrals $\to$ pions) satisfy selection rules which allow tests of CP invariance. A short note has been prepared[23] setting forth expectations for such tests. (This work was begun during the author's stay at the Aspen Center for Physics.)

Multiplicities in decays of charmed particles (with B. W. Lee and C. Quigg)

A systematic study was begun of the multiplicities associated with heavy particle weak decays. It was found that the soft-pion estimates of Ref. 18 could not hold literally: for one thing, the matrix elements for multi-pion decays cannot be constant over their kinematic range if certain soft-pion theorems[24] are to be satisfied. Moreover, the mass scale associated with the matrix elements in Ref. 18 seems to be too large: the multiplicity distributions predicted there for a 4 GeV particle seem to be fairly close to those observed for the new mesons at 1.87 GeV/c^2. In light of this, work was begun to fix the predicted average multiplicity on independent grounds, and then to assume or derive the shapes of distributions corresponding to this multiplicity. Data on $e^+e^- \rightarrow$ hadrons and $\bar{p}p\rightarrow$hadrons will be used to test these models. This work is still in progress.

Mixing of the Q mesons

If the $J^P = 1^+$ strange mesons are composed of one quark which is very much heavier than the other, they will be approximate eigenstates of j(light quark), just as a hydrogen atom's energy levels are approximately characterized by the total j of its electron. This circumstance would lead to specific predictions for the decays of the two states into $K^*\pi$ and $K\rho$. If the two quarks are nearer to one another in mass, certain models[21] still predict definite mixtures of $^1P_1$ and $^3P_1$ for the two eigenstates, with consequent results for decay modes. These predictions, which were worked out during the author's stay at Fermilab, will be checked and extended, and a short note prepared.[25]

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H. Sato

Nonrenormalization Theorem for the Dilatation Current Anomaly

It has now been known that there are violations of various Ward-Takahashi identities associated with exact or partial symmetries. We may classify the known examples as follows; (1) the partially conserved axial-vector current (PCAC) anomaly, (2) the trace anomaly of the improved energy-momentum tensor and (3) the partially conserved dilatation current (PCDC) anomaly. It was found by Adler and Bardeen that the PCAC anomaly is completely determined by the lowest order triangle diagram in perturbation theory: There are no higher order radiative corrections to the anomaly. (nonrenormalization theorem).

We have found that the similar situation occurs on the PCDC anomaly. When the PCDC anomaly was discovered, it was thought that there is no nonrenormalization theorem for the PCDC anomaly. In fact, if we calculate the PCDC anomaly in perturbation theory, using the energy-momentum tensor naively derived from the Lagrangian, we find nonvanishing higher order corrections to the PCDC anomaly. What is wrong in this calculation is that when we calculate higher order corrections, we have to regularize the unavoidable divergences in perturbation theory. The energy-momentum tensor derived from the regularized Lagrangian is different from the one naively derived from the original Lagrangian. There is additional term in the energy-momentum tensor which depends on regulator masses or the space-time dimension if we apply the dimensional regularization method. In previous calculations, those contributions due to the regularization scheme were not taken into account.

We have calculated the second order radiative corrections to the PCDC anomaly in quantum electrodynamics, and found that the second order corrections are exactly cancelled out if we take into account correctly the contributions due to the regularization procedure.

We have generalized the proof of the nonrenormalization theorem for the PCDC anomaly using the Callan-Symanzik equation and the short distance expansion of the products of local operators.

The PCDC anomaly is connected to the high energy limit of the ratio R of the hadronic to muonic cross sections for e^+e^- annihilations through the Crewther's relation. The nonrenormalization theorem for the PCDC anomaly implies that R is directly related to the charges of the constituent particles as long as the Crewther's relation holds.

James Brandt

The static classical SU(2) Yang-Mills equations have been investigated for the case of two point sources at ± d on the z-axis:

$$(\partial_\mu - g\,\vec{A}_\mu\, x)\vec{F}^{\mu\nu} = g\delta_0^\nu\ \vec{\rho} \qquad \vec{\rho} = \vec{t}_A\,\delta\,(\vec{x} - \vec{d}\,) + \vec{t}_B\,\delta\,(\vec{x} + \vec{d}\,)$$

$$\vec{A}_\mu = (A_\mu^a)\ ,\ a = 1,\ 2,\ 3 \quad \partial_0\vec{A}_\mu = 0$$

These equations can be simplified considerably by imposing symmetry conditions on the solutions. The symmetries assumed are: rotations around the z-axis, rotations through angle π about axes in the x-y plane, parity, and time-reversal invariance. Application of one of these transformations to a solution is required to change the solution at most by a local or global gauge transformation. The internal space is taken to be a model for the color space of SU(3) color gauge theories, so that the orientation of the system in the internal space is not detectable and the transformed solution is physically equivalent to the original even if the gauge transformation is global. The spatial symmetries imply that in an appropriate gauge the potentials A_μ^a depend only on ρ and z , with definite z-parity, and either $A_\phi^a = 0$ or $A_\rho^a = A_z^a = 0$. Time-reversal implies that in an appropriate gauge $A_i^{1,2} = 0$, $A_0^3 = t_A^3 = t_B^3 = 0$.

For the case $A_\phi^a = 0$, the equations reduce to the form:

$$A_0^1 = \phi_1 \quad A_0^2 = \phi_2 \quad A_i^3 = (\vec{A})_i$$

$$-\nabla^2\phi_1 + 2g\,\vec{A}\cdot\vec{\nabla}\ \phi_2 + g\,(\vec{\nabla}\cdot\vec{A})\,\phi_2 = g\,\rho_1$$

$$-\nabla^2\phi_2 - 2g\,\vec{A}\cdot\vec{\nabla}\ \phi_1 - g\,(\vec{\nabla}\cdot\vec{A})\,\phi_1 = g\,\rho_2$$

$$\vec{\nabla} \times (\vec{\nabla} \times \vec{A}) = \vec{J} = g\,(\phi_1\vec{\nabla}\ \phi_2 - \phi_2\vec{\nabla}\phi_1) + g^2\,(\phi_1^2 + \phi_2^2)\,\vec{A}$$

The remaining gauge freedom of rotations around the 3-direction of the internal space allows elimination of one additional component of $\vec{A}$ or $\phi_{1,2}$. In gauges of the form $\vec{\nabla}\cdot\vec{A} = 0$, $A_z = 0$ etc., the source $\rho_{1,2}$ contains a parameter θ which is the angle between the "isospins" t_A and t_B. Unlike the abelian case, the equation associated with the eliminated component of $\vec{A}$ is non-trivial and must be retained. The condition $\phi_1\rho_2 - \phi_2\rho_1 = 0$, which states that the potential ϕ must be parallel to the source wherever the latter is non-vanishing, is derivable from the full set of equations but not from a subset. Alternatively, if the equation associated with the eliminated component of $\vec{A}$ is satisfied on a surface in 3-space, it can be derived elsewhere from the remaining equations and the parallel condition.

The presence of four equations for three field components may mean that θ is not arbitrary. For $\theta = 0,\pi$, there are pure Coulomb solutions with $\vec{B} = \vec{\nabla} \times \vec{A} = 0$. Numerical solution of the above equations for the case of a line of charge rather than point sources has shown the existence of non-Coulomb solutions in which the field falls slowly at large distance, confining the electric potential to small ρ. For the point charge case, in the gauge $A_\rho = 0$, an approximate version of the equations in which $A_z = A_z(\rho)$ and the current $\vec{J}$ is averaged over a large distance in the z-direction, has been investigated. The parallel condition is satisfied by assuming that $\phi_{1,2}$ are Coulomb-like near the sources with $A_z(0)$ finite, while the ρ-component of the $\vec{A}$-equation disappears in the averaging. Non-Coulomb numerical solutions have been found for $0 < \theta < \pi$ in which $B \sim \rho^{-1}$ and the electric potential falls faster than Coulomb for large ρ or z. The situation near $\theta = 0,\pi$ is still unresolved.

H. Courant, Y. Makdisi, E. Marquit, M. Marshak, E. Peterson, K. Ruddick

The experimental high energy group at the University of Minnesota has concentrated its efforts on the investigation of the strong and electromagnetic interactions of hadrons. During the past year, the group has extensively studied the spin dependence of several reactions using the Argonne ZGS polarized proton beam, measured the angular and energy dependence of large angle elastic scattering, searched for ψ meson production near kinematic threshold in the reaction $\pi^- p \rightarrow \psi n$ and commenced apparatus construction for a study of coherent Coulomb production of vector mesons at FERMILAB. Some of these studies, such as the elastic scattering cross-section measurements, are second-generation experiments intended to determine very precisely rates and asymmetries for known processes. This type of measurement is useful for testing existing and proposed models and adds to our general knowledge about the interactions of elementary particles. The other experiments, such as the ψ search and some of the polarization measurements, are more speculative in nature. They attempt to determine quantities which have never been measured in an effort to stimulate new approaches toward our understanding of particle physics.

During the period October 1, 1975 to September 30, 1976, the Minnesota high energy group collected data for six months of beam time at the Argonne ZGS—three months of unpolarized beam and three months of polarized beam. In the same period five experiments were proposed and approved at the Argonne ZGS (407, 408, 414, 415 and 418); data collection was completed for four experiments, including one begun in the previous year (365, 407, 408, and 414). Analysis of all completed experiments has continued during the year; more than a dozen interim reports have been given at appropriate meetings and final results from portions of two experiments have been published (see bibliography). At the Argonne ZGS, the Minnesota group has collaborated with physicists from Argonne, Columbia, Indiana, Rice, and UCLA, with Minnesota in each case providing the majority of the experimental apparatus and manpower. The collaboration for FERMILAB experiment 272 includes physicists from Minnesota, FERMILAB and the University of Rochester.

The significant physics results of the past year can be divided into three categories: 1) Elastic Scattering at Large Angles, 2) Polarization Studies and 3) Vector Meson Production. Even though these experiments used the same core apparatus, the physics goals are sufficiently divergent that we shall discuss each of them separately.

Elastic Scattering at Large Angles

The motivations for Argonne experiment 365 were to make high resolution measurements of $\pi^{\pm}$, $K^{\pm}$, $\bar{p}$ and p elastic scattering from protons near 90^0 in the center-of-mass frame, to test the application of the Ericson-Frautschi fluctuations model in πp scattering and to determine the s dependence of the $\theta^* = 90^0$ cross-section for several reactions in order to determine the validity of parton models. This experiment completed data collection in April, 1976. Continuous measurements were made over the incident momentum ranges of 1.8 to 9.8 GeV/c for negative particles and 1.8 to 7.1 GeV/c for positive particles. More than 2 x 10^7 events were recorded on magnetic tape and all of these events have been reconstructed and have had their geometry analyzed. At this point only a fraction of the data has been used to determine preliminary cross-sections.

The major conclusions that we have drawn at this preliminary stage of the analysis were discussed at the Tblisi Conference. They are:

A) We find no evidence for the large fluctuations in π^+p scattering at p_0 = 5 GeV/c, which were previously reported by a CERN group. (See Figures 1 and 2). To draw this conclusion, we have scanned a large range of incident momenta to insure that we have not missed some sharp structure due to an error in the absolute momentum calibration.

B) We do find differences in the πp elastic cross-sections at constant t when the cross-sections are separated by about a pion mass in the available c.m. energy. (See Figure 3). We interpret these differences as evidence of the type of fluctuations that are consistent with the Ericson-Frautschi model, assuming some reasonable density of states function for the πp resonances. We expect to use our final cross-section data to determine some of the properties of the ensemble of resonances by use of this model.

C) The overall dependence of the 90^0 πp cross-section is close to s^{-8}, but the shape is modified by what appears to be a diffraction pattern. We have clearly observed the first diffraction minimum at $s \simeq 8$ $(GeV)^2$ and we have some evidence for a second minimum at $s \simeq 11$ $(GeV)^2$. (See Figure 4). We are currently analyzing the data with an incident $K^{\pm}$ or $\bar{p}$. Our pp data at 90^0 is in good agreement with previous measurements.

Polarization Experiments

The University of Minnesota has become one of the foremost groups studying the physics of spin at the Argonne ZGS. The experiments for which data have already been collected include measurements of meson production asymmetries in $p\uparrow p$ and $p\uparrow n$ collisions at p_0 = 6 and 12 GeV/c, measurement of pp elastic polarizations at small $|t|$ at p_0 = 6 GeV/c, a study of asymmetries in reactions $p\uparrow p \rightarrow d + X$, measurements of the analyzing power and depolarization parameters in $p\uparrow p \rightarrow p + X$ and $p\uparrow n \rightarrow p + X$ and a determination of the polarization parameters in $p\uparrow + {}^4He$ elastic scattering. These studies comprise Argonne experiments 393, 407, 408 and 414. They collected data in September 1975 and February, May and August 1976.

Some of the polarization data has already been published in final form. The major conclusions from both the published and unpublished data are:

A) The first measurements of pion production asymmetries in $p\uparrow p$ collisions show several surprising features. The asymmetries are identical where this is kinematically permitted at p_0 = 6 and 12 GeV/c when plotted as a function of u, the square of the four-momentum transfer between incident proton and outgoing pion. (See Figure 5). The observed asymmetries, when plotted as a function of u, appear dependent on X (the Feynman scaling variable) only in magnitude but not in shape. Thus, the asymmetries at small x appear to be "diluted" by approximately isotropic pion production. In addition, the shape of the asymmetries for both π^+ and π^- production appear similar to the polarizations observed in $\pi^{\pm} p$

backward elastic scattering. We have hypothesized that the data can be explained in terms of baryon exchange between an incident proton and virtual pion associated with the target proton.

B) Our measurements of the polarization parameter in pp elastic scattering of 6 GeV/c have improved errors over the existing data at small $|t|$. All of the world data from both polarized beam and polarized target experiments for $|t| < 0.5\ (\mathrm{GeV/c})^2$ can be fit by the empirical relation $P = (0.481 \pm 0.010)\sqrt{-t}\exp(2.291 \pm 0.085)t$. (See Figure 6). Without any normalization adjustments among three experiments, this fit yields a χ^2 of 38 for 33 degrees of freedom.

C) At 6 GeV/c, the polarization in the reaction $p\uparrow + p \rightarrow d^+ \rightarrow \pi^+$ is small or zero for small $|t|$ which contrasts sharply with recent Regge predictions. The data can be fit, however, by a very naive Regge model which assumes that all spin flip amplitudes vanish in this baryon exchange process. The lack of large asymmetries, however, is not some obvious property of the deuteron. The process $p\uparrow + p \rightarrow d^+ \rightarrow X^+$ shows a negative asymmetry of about 20 percent in the region where the missing mass corresponds to a ρ^+ meson.

D) The depolarization parameter (D) is a measure of the unnatural parity exchange present in the pp scattering process. In particular, if $D \approx 1$, the unnatural parity contribution is small. Preliminary data from our measurements at 6 GeV/c show that $D \approx 1$ for elastic scattering, but that D drops sharply toward zero for the reaction $p\uparrow + p \rightarrow p + X$ when the missing mass is near the N^* (1232). At higher missing masses, D rises again and slowly drops towards zero for $m_X > 2$ GeV/c.. D measurements from deuterium target yield similar results indicating similar unnatural parity contributions to pp and pn scattering.

E) The polarization parameter in p-^{4}He elastic scattering depends both on the structure of the nucleon-nucleon amplitudes and multiple scattering corrections due to the structure of the ^{4}He nucleus. The preliminary data shown on the cover of this report and in Figure 7 show large dips in the polarization whose location is fixed in t, but whose size varies with the incident momentum. Particularly, at 1.2 GeV/c incident momentum, the data agree well with Glauber model calculations. At higher incident momenta, the p^{4}He data will place constraints on the nucleon-nucleon amplitudes, which are being determined in other experiments, as well as add to our knowledge of the ^{4}He nucleons.

Vector Meson Production

In Argonne experiments 305 and 411, we have studied the production of ϕ and ψ mesons, respectively, near their kinematic threshold for production in π^-p collisions. E-305 detected ϕ mesons by their decays in K^+K^- pairs; E-411 was sensitive to both the e^+e^- and $\mu^+\mu^-$ decay modes of the ψ meson. Detection of the ψ in this experiment would be its first observation in an exclusive hadronic channel. Calculations suggested that we would observe the ψ , if, similar to the ϕ meson, it had a threshold enhancement in the π^-p channel. Data were collected for the ϕ meson at incident momenta of 1.6, 1.7, 1.8, 2.0 and 2.2 GeV/c and for the ψ meson at 8.2 and 9.8 GeV/c.

The major conclusions of these experiments are:

A) We have no evidence for any ψ events in the $\mu^+\mu^-$ channel. This null observation corresponds to an upper limit of $\approx$ 3 nb at the 90% confidence level. We are currently analyzing the e^+e^- channel. If no ψ events are found with this decay mode, the sensitivity of the experiment implies an upper limit of $\approx$ 1 nb at the 90% confidence level for this process.

B) Near threshold, we observe a definite enhancement in the K^+K^- mass spectrum corresponding to the ϕ meson (Figure 8). The observed mass of 1021 ± 3 MeV and the observed width of 8 ± 2 MeV are consistent with accepted values for the ϕ using an experimental resolution of 4 MeV. The differential cross-section is flat in t, which suggests that the threshold enhancement is possibly due to an s-channel resonance or to an exotic or double particle exchange. The total cross-section for $\pi^- p \rightarrow \phi n$ (Figure 9) falls off as s^{-11} above an incident momentum of 2 GeV/c.

Coherent Coulomb Production at FERMILAB

Progress has been made during the past year toward the completion of the apparatus for FERMILAB E-272 , which seeks to study the symmetries among vector mesons by a measurement of their electromagnetic couplings. Since these couplings are small, the most accurate method of determining them is by observation of coherent Coulomb production processes such as

$$\pi + Z \rightarrow \rho + Z$$
$$K + Z \rightarrow K^* + Z$$

rather than by study of decays such as $\rho \rightarrow \pi\gamma$. The proposed apparatus is a high-resolution forward spectrometer with good neutrals detection from a lead-liquid argon calorimeter. The particular responsibilities of the Minnesota group in the collaboration are the drift and proportional chamber electronics, the veto and trigger counters outside the target vacuum box and the off-line analysis programming.

Until now, we have concentrated our efforts on the long lead-time aspects of the experiment such as securing sufficient funding to make the experiment viable, obtaining laboratory approval for Summer 1977 installation and testing drift chambers and related electronics. In the past year, grants from the National Science Foundation and the University of Minnesota have assured sufficient funding for the experiment provided that reasonable support is forthcoming from ERDA. Toward that end, we have submitted a supplementary proposal to ERDA for 1976. A draft agreement has been completed by the experimenters and has been submitted to the laboratory for approval, which is expected shortly. We have built four prototype drift chambers and associated electronics and are now engaged in testing them using a PDP 11/03 system which we have obtained for our laboratory in Minneapolis using University funds. We have also tested the LeCroy drift chamber digitizing system and have decided to use it pending a final test of a revised module this fall. Our collaborators have performed tests at Cornell of a prototype of the lead-liquid argon calorimeter. The resolution obtained was about 12 percent/ $\sqrt{E}$, which is more than adequate for our experiment.

The Minnesota high energy group, during the past year, has become one of the dominant users of the Argonne ZGS, and one of the major groups studying polarization phenomena throughout the world. As part of this role, members of the group have served on Technical Advisory Panels at Argonne and represented Argonne users in presentations to ERDA and AUA review panels. One member of the group was also Chairman of the Organizing Committee of the Symposium on High Energy Physics with Polarized Beams and Targets held at Argonne on August 23-27, 1976. Almost 200 physicists from North America, Europe, Japan and the Soviet Union attended this conference to communicate the most recent information about the study of spin in high energy physics. The proceedings of the conference, to be published by the American Institute of Physics, is now in preparation at the University of Minnesota.

E. Coleman

Photoproduction Experiments at Fermilab (With M. Marshak)

In collaboration with MIT a photoproduction experiment (E-263) is being constructed. The primary goal is to measure phi photoproduction as a function of incident photon energies and momentum transfer. Although this primary goal remains unchanged, the same apparatus is proposed to detect narrow resonances similar to the J/psi particle discovered at BNL and SPEAR. Many speculations persist that long-lived particles, similar to the J/psi particle may exist. Some of the particles may have quantum number $J^P = 1^-$ just as the photon and the psi; and consequently, they may be diffractively produced in photoproduction. A measurement of this production as a function of incident photon energy and momentum transfer could settle the important question of whether these particles can be diffractively produced. For charged narrow resonances there is a possibility that charmed particles could be detected through weak decays. In this case, one would expect an unusually large number of strange particles in the final state.

The magnetic spectrometer used in this experiment is well suited to the measurement of narrow resonances. The two large aperture multiple tube Cerenkov counters can distinguish pions and kaons up to 120 GeV and can detect a maximum of 16 final state charged particles simultaneously. With shower counters behind the Cerenkov counters, one could also detect electromagnetic particles such as electrons, gammas, neutral pions, etas, etc.

The acceptance of the spectrometer allows the measurement of relatively large angles. Three sets of drift chambers around the liquid hydrogen target will detect a recoil particle. Two dipoles will bend the desired forward particles horizontally to focus the particles at a point 120 downstream of the target. Four proportional chambers and two drift chambers will measure the momentum of the forward particles. The Cerenkov counters are used to separate the kaons and protons from the pions and electrons. The shower counters placed behind the Cerenkov counters should achieve a rejection ratio of 10^{-3} for electrons or positrons having energies greater than 6 GeV. A Monte Carlo program was used to calculate the resolution of the spectrometers. For 100 GeV photo-production of the psi at a four-momentum transfer at 0.1 GeV/c and $t = 0.01$ GeV^2 a mass resolution of ± 8 MeV and momentum resolution of ± 6 GeV/c is achieved. If a dip is found in the distribution, the t resolution can be improved by moving the magnets slightly apart.

To discriminate against inelastic events for four-momentum transfers greater than 0.1 GeV^2 three sets of chambers around the liquid hydrogen target measure the scattering angles of the recoil proton. This system provides two useful constraints: coplanarity and two independent measurements of the four-momentum transfers. Monte Carlo results show that the coplanarity requirement is sufficient to reject background of N^* and two pion production to the 0.1% level if these background channels have the same cross section as phi production. It is expected that E-263 will run at Fermilab during the summer of 1977. A substantial portion of the apparatus will be needed by the Santa Cruz experiment which is scheduled before this experiment. Consequently, all components should be received by the spring of 1977.

Neutral Kaon Interactions (with J. Lee)

In collaboration with the Universitat Heidelberg and Tel-Aviv University a total of 2.4 million pictures of neutral kaon interactions are being analyzed. These pictures were taken in the DESY 85 cm liquid hydrogen bubble chamber. Superposition of phase space and Breit-Wigner resonance distributions was used to determine preliminary values of the photon cross section. A new measurement of the life-time of the short-lived kaon and of the lambda are being sought and indications of (1520), (1405), (1910), (1940), (2030), and (2100) production are being investigated. Studies of short-lived kaon production from long-lived kaons are being performed to determine the regeneration-phase angle and the intercept of the effective trajectory. These measurements provide data on omega exchange and the non-flip coupling of vector mesons to baryons. The large number of pictures with a long-lived kaon momentum spectrum between 0.5 and 2.5 GeV/c for 80% of the kaons permits the acquisition of moderate statistics for a wide variety of final states with a significant range of kinematic parameters.

Inelastic Hadron-Deuteron Interactions

Experimental data for proton-deuteron, pion-deuteron, and kaon-deuteron scattering is being analyzed from 2 GeV/c to the highest available incident particle energies. A major purpose of this investigation is to analyze the deuteron wave functions by determining the relationship between the particle nucleon amplitude and the particle-deuteron scattering amplitude. Several models of high energy scattering are applied to this process. Suitable dynamical models of production processes and final states interactions are being tested and extentions of high energy eikonal models are being investigated.

Muon Pair Production at PETRA (with M. Marshak)

A proposal (P-76/15) has been submitted to DESY for the measurement of electron-positron reactions at high energies. In collaboration with MIT and DESY we propose to measure muon pair production over 4π solid angle using a spectrometer rotatable in polar angle and azimuthal angle. The system includes magnetized iron muon detectors, hadron calorimeters, shower counters, and proportional counters mounted at one intersection region of PETRA. The apparatus will measure μ^+, μ^- asymmetries to look for weak and electromagnetic interference effects and to look for $e^+e^- \rightarrow e^-\mu^+ + \eta\nu$ and other rare effects using the 19 GeV x 19 GeV electron-positron storage ring. A decision on this proposal is expected during FY 1977.

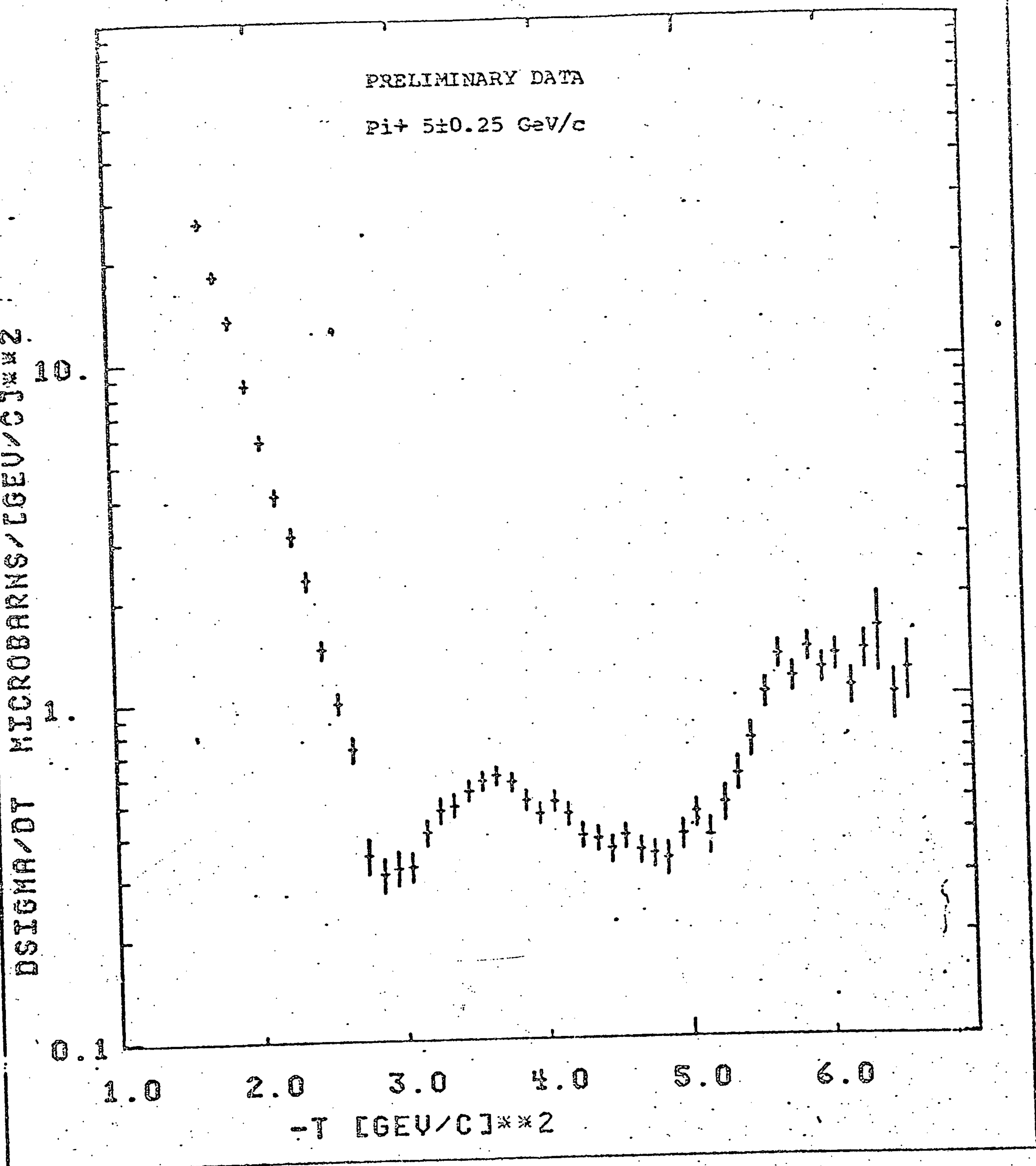


FIGURE 1--The differential cross-section $d\sigma/dt$ as a function of $-t$ for π^+p elastic scattering at p_o = 5 GeV/c

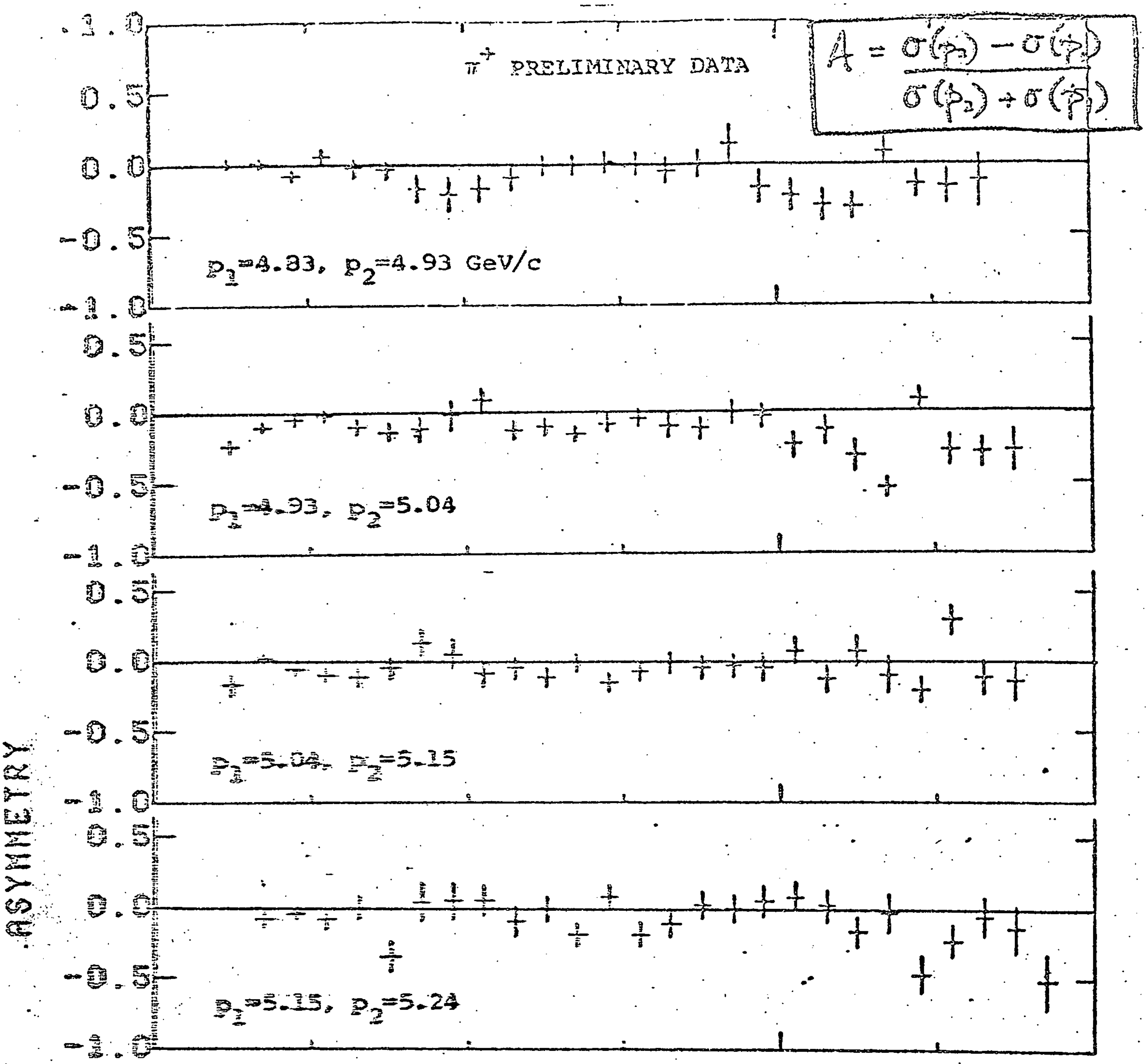
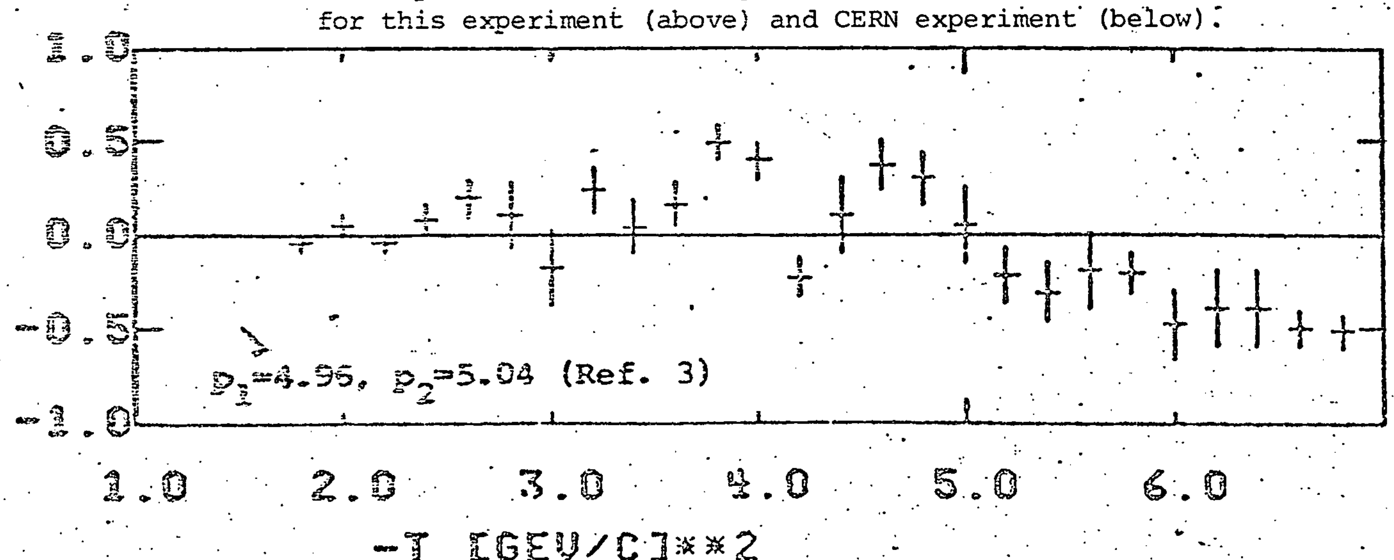


FIGURE 2--The asymmetries between adjacent incident momentum bins in π^+p scattering for this experiment (above) and CERN experiment (below).



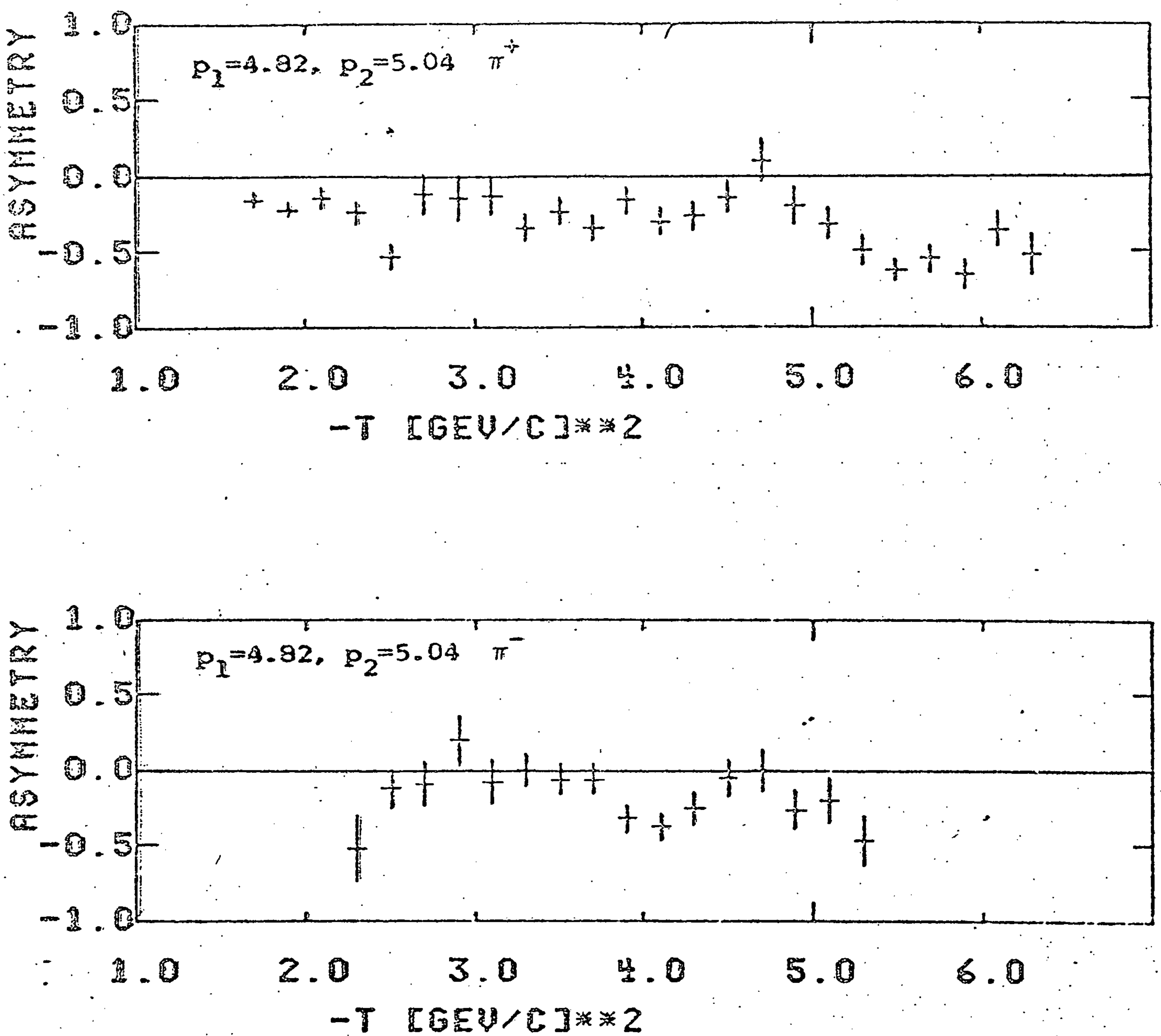


FIGURE 3--The cross-section asymmetries, calculated by the equation in Fig. 2, for πp scattering for incident momenta separated by a pion mass in the available c.m. energy.

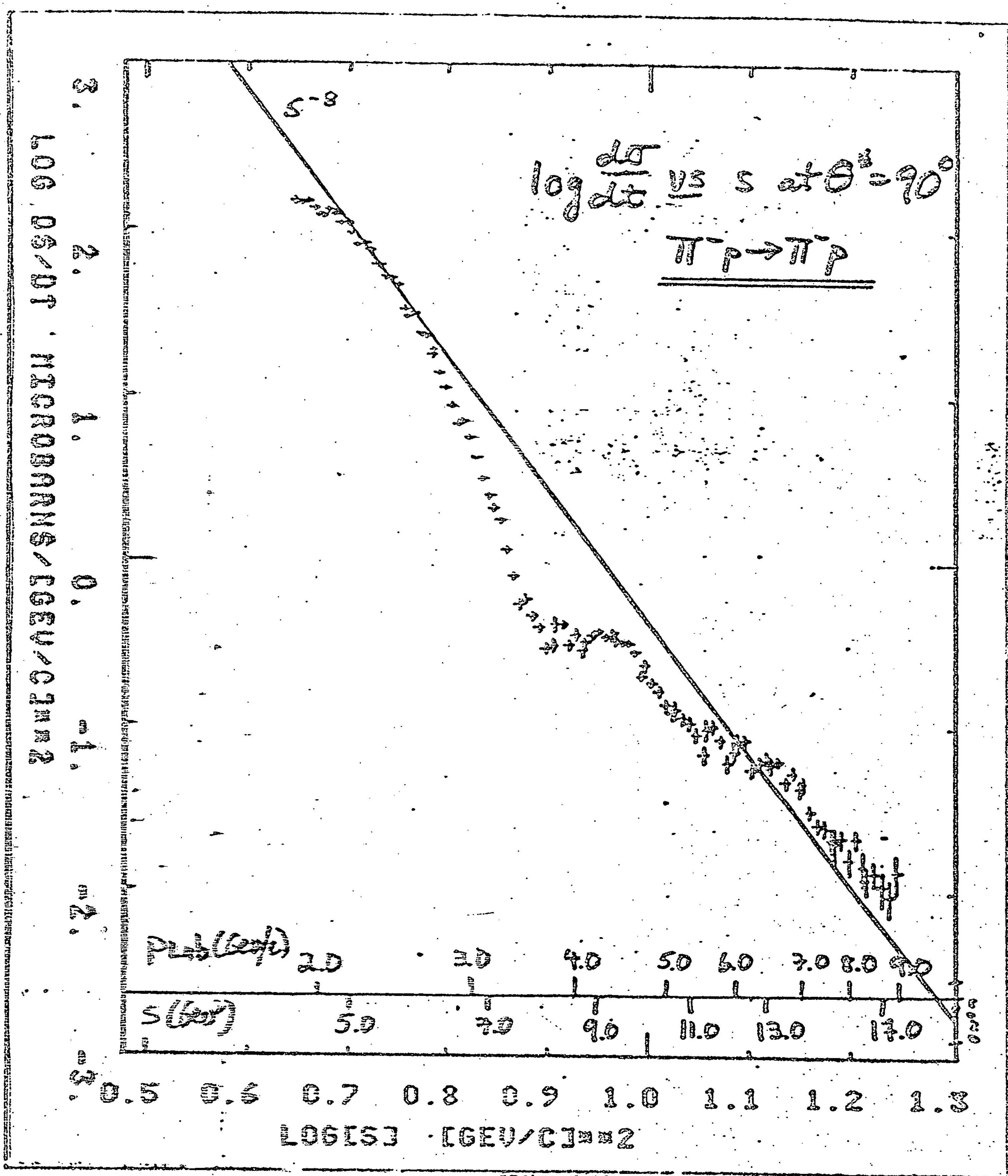


FIGURE 4--The $\theta^* = 90^\circ$ cross-section for $\pi^- p$ elastic scattering as a function of s, the square of the center-of-mass energy.

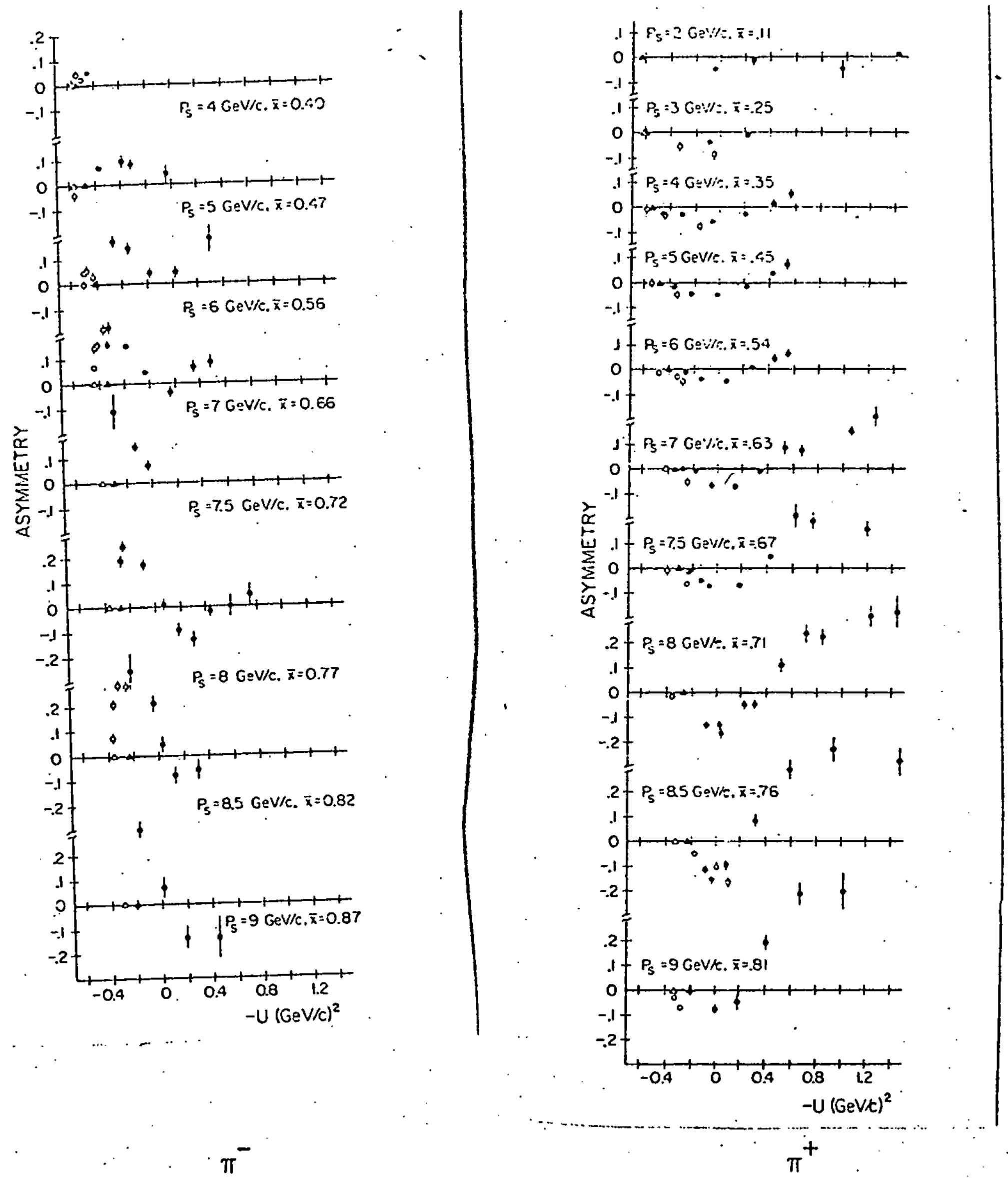


FIGURE 5-- The polarization asymmetries for the inclusive production of pions in the reaction $p + p \rightarrow \pi^{\pm} +$ anything at incident momenta of 6 and 11.8 GeV/c.

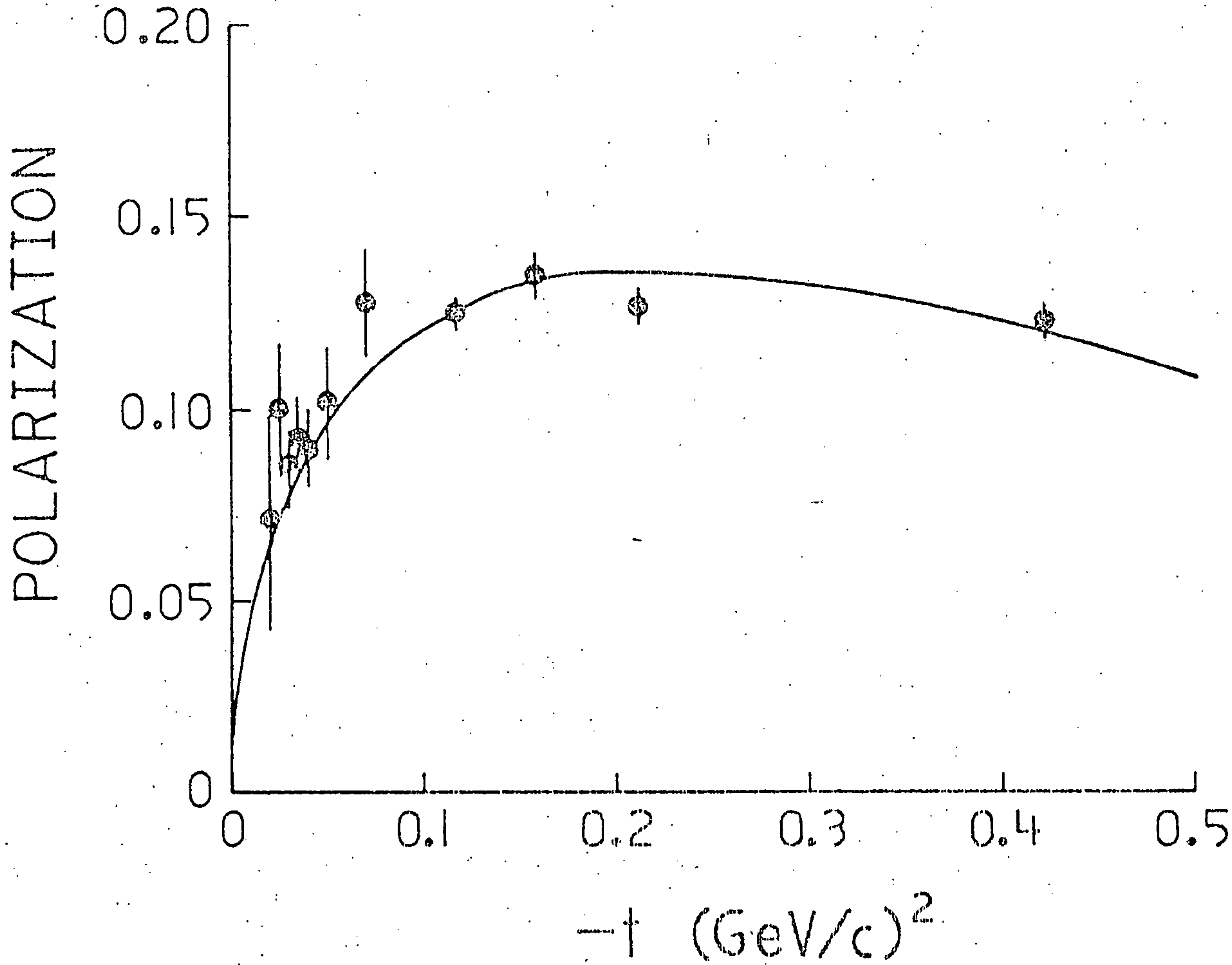
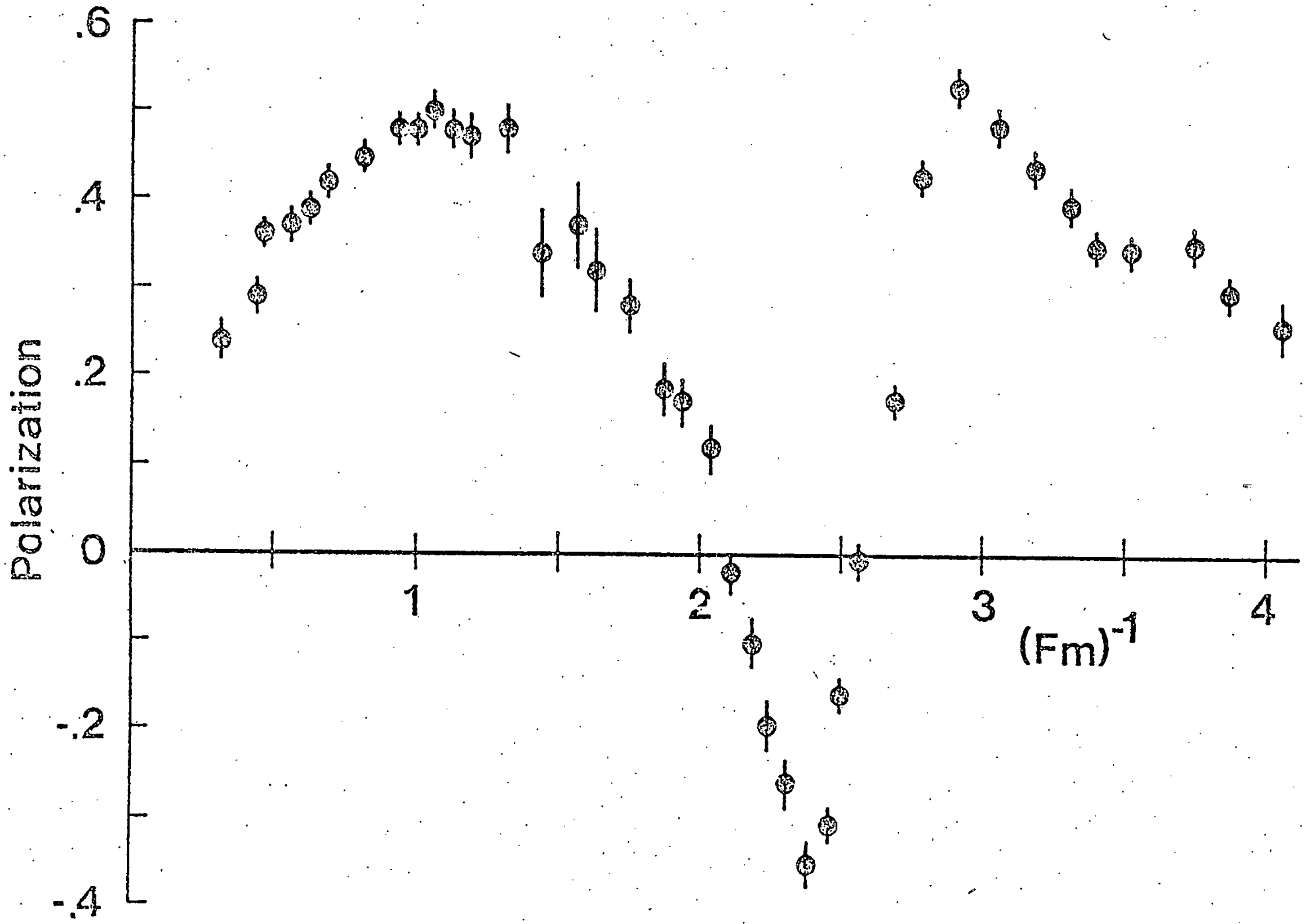


FIGURE 6--The polarization in pp elastic scattering at 6 GeV/c. The circles are the results from E-393; the line represents a fit to all of the world data.

FIGURE 7--The polarization asymmetry in $p\,^4He$ elastic scattering at an incident momentum of 1.2 GeV/c. These are preliminary data from Argonne E-414.



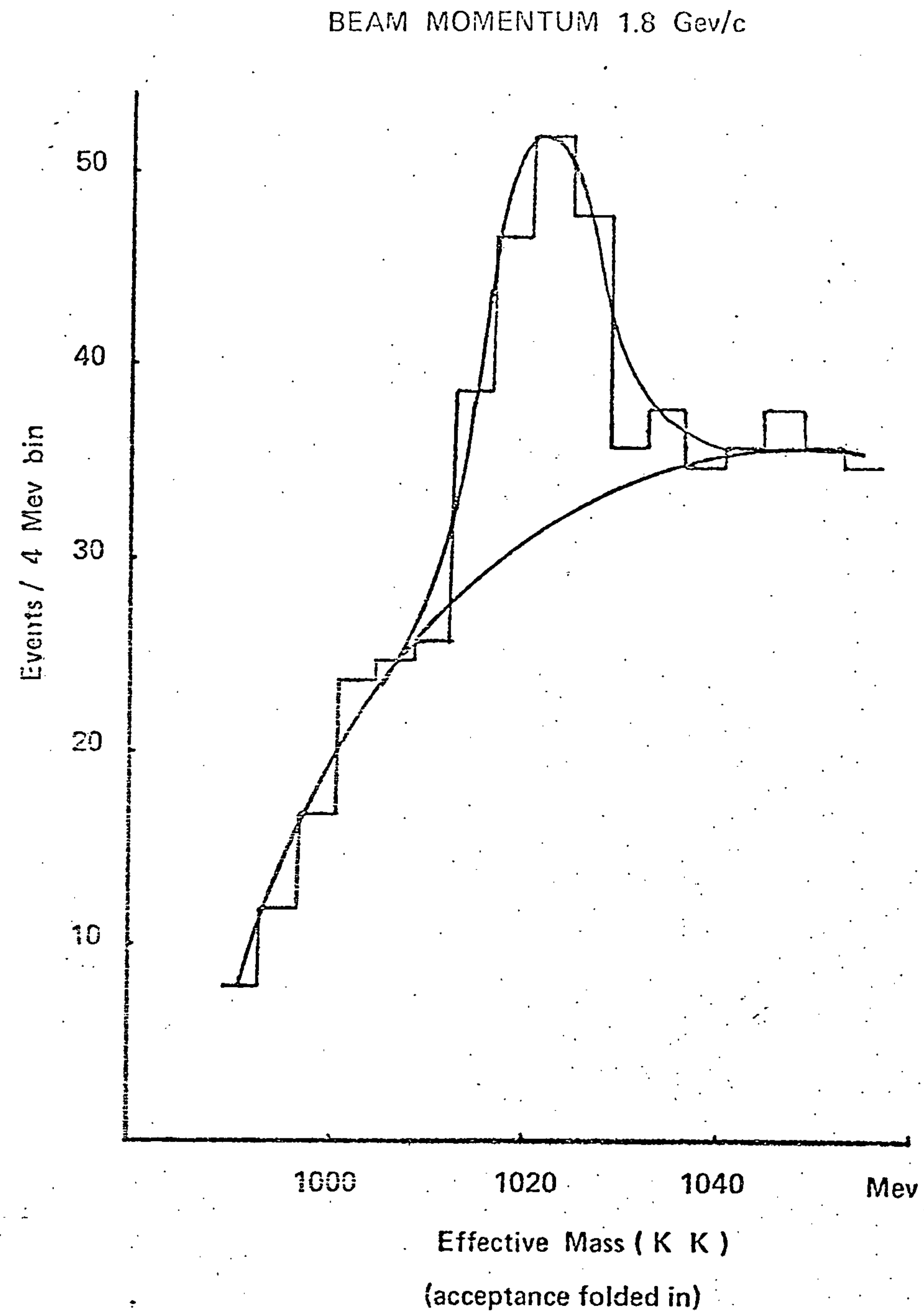


FIGURE 8--The ϕ peak in the effective mass in the reaction $\pi^- + p \rightarrow K^+ + K^- + n$ at an incident momentum of 1.8 GeV/c. These data are from Argonne E-305.

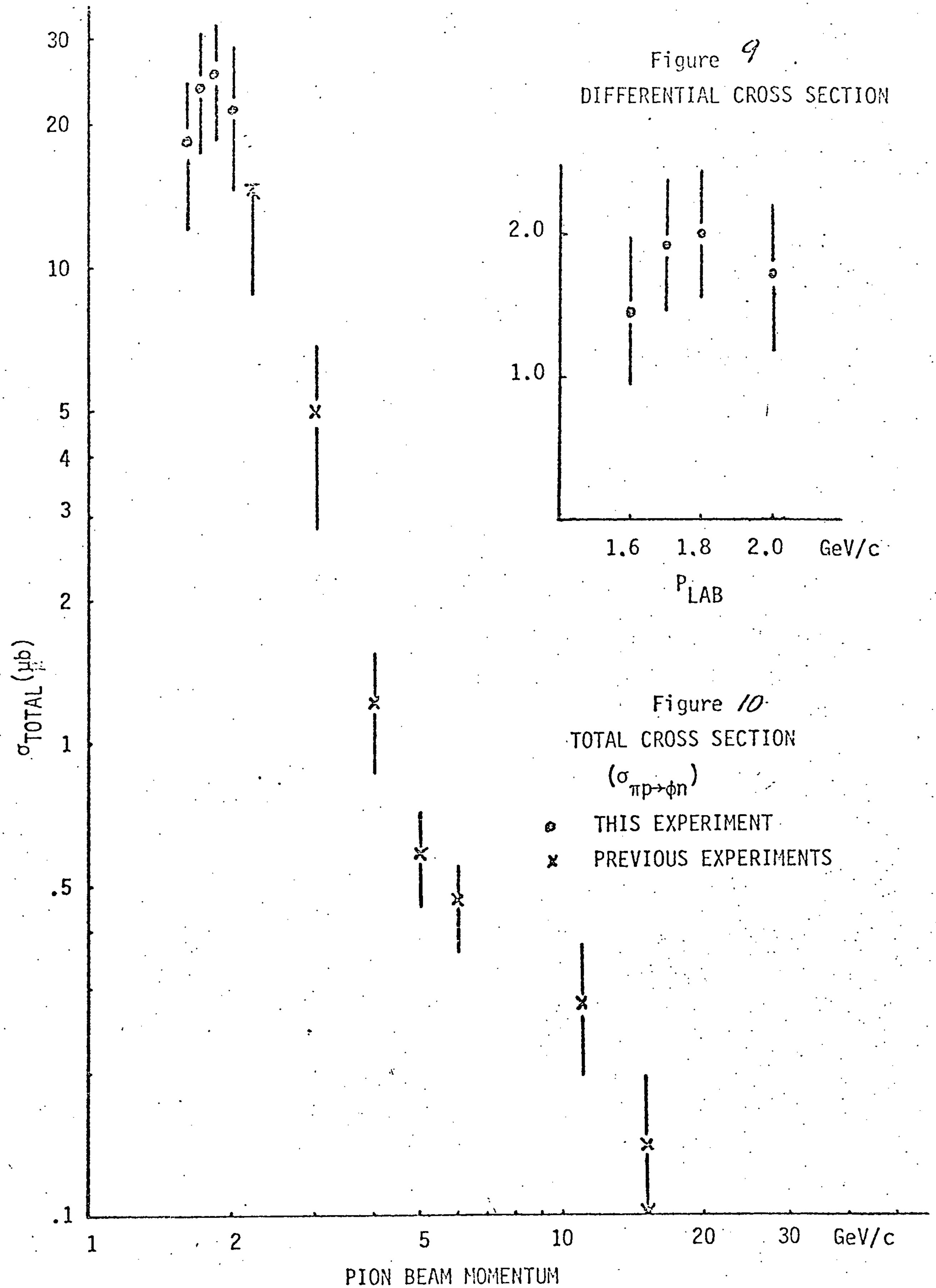


FIGURE 9--The total cross-section for ϕ production in the reaction $\pi^- + p \rightarrow \phi + n$.

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COO-1764-226 "Resonating-group calculation of n + ^{3}H Scattering", M. LeMere, R. E. Brown, Y. C. Tang and D. R. Thompson, Phys. Rev. C12, 1140 (1975).

COO-1764-227 "Resonating-group study of N + ^{16}O Scattering with a generator-coordinate technique", D. R. Thompson and Y. C. Tang, Phys. Rev. C12, 1432 (1975).

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COO-1764-233 "Investigation of the $(d_{5/2})^2$ and $(d_{5/2}s_{1/2})$ Two-Particle Configurations in ^{18}O using the ^{17}O(d,p)^{18}O Reaction at 18 MeV", P. J. Ellis (with T. K. Li, D. Dehnhard and R. E. Brown), Phys. Rev. 13C, 55 (1976).

NEW PUBLICATIONS

COO-1764-243 "Measurement of Pion Asymmetries in Inclusive Proton-Proton Scattering at 6 GeV", by M. Marshak et.al. and R. D. Klem, Argonne Nat. Lab., High Energy Physics Report.

COO-1764-244 "Measurement of Pion Asymmetries in Inclusive Proton-Proton Scattering at 6 and 11.8 GeV/c", M. Marshak, et.al., Phys. Rev. Lett. 36, 929 (1976).

COO-1764-245 "Single-Quark Transition Analysis of Resonance Photocouplings", J. Rosner and J. Babcock, to be published.

COO-1764-246 PROGRESS REPORT

COO-1764-247 "Polarization in pp elastic scattering at small t", M. Marshak et.al., submitted to Phys. Rev. D.

COO-1764-248 "Model of the Behavior of Solid Objects during Collision", B. Bayman, Amer. Journ. of Phys. 44, no. 7, July 1976, p. 671.

COO-1764-249 "Theory of Hitches", B. Bayman, to be published.

COO-1764-250 "Absence of Higher Order Corrections to the Dilatation Current Anomaly", H. Sato, submitted to Phys. Rev. Lett.

COO-1764-260 "Nonrenormalization Theorem for the Dilatation Current Anomaly", H. Sato, submitted to Phys. Rev.

COO-1764-261 "Comment on New Methods for Solving the Bethe-Goldstone Equation", S. F. Tsai, (with T. T. S. Kuo) Phys. Rev. C., Oct. 1976.

COO-1764-262 "Response Function Formalism in the Random Phase Approximation with Skyrme Interactions", S. F. Tsai, to be published.

COO-1764-263 "An Energy Dependent Chou-Yang Model with the Y-Graph Correction", D. A. Geffen (with D. Coon and J. Tran Thanh Van), to be submitted to Physical Review.

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COO-1764-265 "Study of the α + ^{16}O System with the resonating-group method", M. LeMere, Y. C. Tang and D. R. Thompson, Phys. Rev. C14, 23 (1976).

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COO-1764-268 "Resonating-group Study of the N + ^{40}Ca System", D. R. Thompson, M. LeMere and Y. C. Tang, will appear in Nucl. Phys.

COO-1764-269 "Influence of the Pauli Principle on the Optical Potential for α + ^{16}O Scattering", R. A. Partridge, Y. C. Tang, D. R. Thompson and R. E. Brown, will appear in Nucl. Phys.

COO-1764-270 "On the use of α + α Scattering to Study the Nucleon-nucleon interaction", R. E. Brown and Y. C. Tang, will appear in Phys.Rev.

COO-1764-271 "Study of d + ^{16}O and N + ^{16}O System with the resonating-group method", M. LeMere, Y. C. Tang and D. R. Thompson, will appear in Phys. Rev.

COO-1764-272 "$^{16}O(d,{}^{3}He)^{15}N$ Reaction at E_d = 29 MeV; Reaction Mechanism and Nuclear Structure", A. Dudek-Ellis and P. J. Ellis (with M. A. Firestone, J. Jänecke and T. Engeland), Nuclear Physics A258, 317 (1976).

COO-1764-273 "Comment on the Quadrupole Moment of the First-Excited 2^{+} State of ^{18}O", P. J. Ellis (with T. Engeland), Phys. Rev. Lett. 36, 994 (1976).

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COO-1764-279 "Mixing of Neutral mesons and tests for CP Violation in their Decays", J. Rosner (with M. Goldhaber), to be submitted for publication, IAS COO-2220-86, October 1976.