PHYSICS WITH POLARIZED BEAMS*

Report of the ANL Technical Advisory Panel

November 1975

Panel Members and Consultants:

G. Kane	Michigan (Chairman)
E. L. Berger	ANL
R. D. Field	Cal Tech
D. Miller	Northwestern
P. Pirila	ANL
J. Pumplin	Michigan State
D. Rust	Indiana
B. Sandler	ANL
P. R. Stevens	Cal Tech
K. Terwilliger	Michigan
G. H. Thomas	ANL
A. B. Wicklund	ANL
A. Yokosawa	ANL

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

*Work performed under the auspices of the U. S. Energy Research and Development Administration

Table of Contents

	Page
I. Introduction	1
II. Basic Report	2
III. Detailed Appendices	
1. Summary of Measurements of the Spin Dependence in NN Interactions from 2 to 12 GeV/c, D. Rust.	11
2. Time Reversal and Parity Tests, K. Terwilliger.	25
3. A Picture Book of Nucleon-Nucleon Scattering: Amplitudes, Models, Double-and-Triple-Spin Observables, R. D. Field and P. R. Stevens.	28
4. Behavior of Low and Medium Energy NN Scattering and Amplitude Reconstruction, G. H. Thomas.	83
5. Polarization in Inelastic "Diffractive" Processes, E. L. Berger	106
6. N [*] Production with Polarized Beam, A. B. Wicklund.	112
7. Inclusive Polarization Measurements at the ZGS, D. Rust	129
8. Polarization in Inclusive Processes, R. D. Field	132

I. Introduction

The polarized proton beam at the Argonne National Laboratory is unique and provides a valuable tool, which when used wisely will improve greatly our understanding of the nature of the interactions of hadrons. In this report we explore what can be learned from polarized beam experiments.

Future experimental studies with polarized beams can be divided naturally into two areas:

1. There are new and largely unexplored areas, where measurements can probe or stimulate ideas, or find new effects. These include

- (a) invariance principles and symmetries,
- (b) exclusive measurements at large momentum transfers (t) or inclusive measurements at large p_T , and
- (c) the low and intermediate energy region connecting the phase shift and high energy regions.

2. There are areas that have been studied but not systematically or in detail, where a complete set of measurements will lead to more powerful constraints on our theories and to a more fundamental understanding of the interaction among hadrons. Examples are

- (a) elastic, two-body, and quasi-two-body reactions at $|t| \leq 1.0 \text{ (GeV/c)}^2$, and
- (b) inclusive reactions at small p_T .

Reports of this type tend to be vague and state essentially that "everything is of equal use." We have attempted to avoid this pitfall and hope to spell out experimental directions which will be the most useful in developing underlying theories of hadronic collisions. As a pedagogical device to accomplish this, we have quoted approximate percentages of a total program which could be devoted to different areas.

Our findings are presented in the form of a short basic report with several long detailed appendices. In the basic report we state our opinion as to the amount of polarized beam experimental effort that should be applied to the following areas: nucleon-nucleon scattering, quasi-two-body processes, inclusive production, and new or unexplored areas (such as large p_T and invariance principles). We discuss our reasoning briefly, however, the details are left for the appendices. In the appendices, members of the panel present certain aspects of the above areas, which should be useful for planning and/or performing polarized beam experiments.

II. Basic Report

We subdivide polarized beam physics into the following categories:

1. $NN \rightarrow NN$, Small t (35-45%)
 - (a) pp Elastic (low, intermediate, and high energies)
 - (b) np Elastic (low, intermediate, and high energies)
 - (c) $\bar{p}p$ Elastic (low, intermediate, and high energies)
 - (d) np and $\bar{p}p$ CHEx (low, intermediate, and high energies)
2. Quasi-two-body Reactions and Spectroscopy (25-35%)
 - (a) Diffractive (i.e. Vacuum exchange allowed)
 - (b) Non-diffractive (eq. $p_{\uparrow}p \rightarrow n\Delta^{++}$)
 - (i) Below 3.0 GeV/c
 - (ii) Above 3.0 GeV/c
3. Inclusive Small t (5-10%)
 - (a) Meson Exchange (eq. $pp \rightarrow pX$, $pp \rightarrow \Delta^{++}X$)
 - (b) Baryon Exchange (eq. $pp \rightarrow \pi X$)

4. New Unexplored Areas (15-25%)

- (a) Large p_T Inclusive
- (b) Large t Elastic
- (c) Invariance Principles (CPT)

We have indicated the percentage of experimental effort that, in our opinion, should go into the four categories and will now discuss how the time should be divided within the categories.

NN $\rightarrow$ NN Scattering ($|t| \leq 1.0 \text{ (GeV/c)}^2$) (Appendices 3 and 4)

The panel agreed that the greatest proportion of experimental effort (35-45%) should go into studying the nucleon-nucleon scattering system at small t . Within this category there are many questions of great interest. By measuring double- and triple-spin observables at say 6.0 GeV/c as a detailed function of momentum transfer, one can determine the nature of the five underlying complex amplitudes that describe pp elastic scattering. There is no other way to isolate these amplitudes. The amplitudes can be compared with existing models (see Appendix 3), which will help clarify our theoretical understanding of the nature of Regge poles and absorption. Existing data on pp elastic scattering cannot even determine (except at $t=0$) whether the natural parity helicity non-flip amplitude dominates over the single and double helicity flip amplitudes as is the case for all Regge models (see Appendix 3 and 4). We must stress, however, that measurements of pp elastic scattering over the ANL energy range should be supplemented with a comprehensive program to measure spin observables at several energies, as well in np elastic, $\bar{p}p$ elastic, and np CHEX. By studying these processes amplitudes of definite quantum numbers (isospin, signature, C-parity) can be determined, and one can expect a major impact on theory.

The importance of the role of quantum numbers can be illustrated by their effect on models for elastic scattering. Existing approaches have been of two kinds, either based on exchanges of mesons carrying t -channel quantum numbers and modified by direct channel rescattering, or direct-channel optical models. The completely optical type models have now been eliminated from consideration by comparison of different reactions. For example, a characteristic property of these models is that the polarization is obtained as the rate of change of the cross section with respect to momentum transfer, $P \approx \sqrt{-t} \, d(d\sigma/dt)/d\sqrt{-t}$. This nicely gives the polarization for $pp \rightarrow pp$. For np elastic, on the other hand, one finds $d\sigma/dt$ equal within errors to that for pp elastic, while P is markedly different in shape and size, and for $\bar{p}p \rightarrow \bar{p}p$ the differential cross section is steeper than for $pp \rightarrow pp$, so it has a larger derivative, but the polarization is smaller in size (and different in shape). The approach based on meson exchanges has no difficulty with the quantum number structure, so the relevant considerations in the appendices are based on this approach.

As described in detail in the appendices, the energy dependence of the amplitudes in the momentum range 2 to 12 GeV/c is important in all models. In Regge exchange models, this energy dependence provides the necessary clues for identifying lower lying singularities (daughter trajectories, Regge cuts, Regge-Regge cuts, etc. ?) to which present data already allude. We feel that it is very important to carry measurements down below 3.0 GeV/c (see Appendix 4). In the region 1.0 - 2.0 GeV/c, a connection with phase shifts can be made. The region 1.0 - 4.0 GeV/c is characterized by rapid energy dependent effects associated with the opening of inelastic channels. Good data on pp , pn , and $\bar{p}p$ elastic scattering in this region would provide useful tests of our theoretical ideas concerning unitarity, duality, and finite-energy sum rules.

In particular, the increased spin leads to more amplitudes and to ways of studying duality and FESR physics that are not available in, for example, πN reactions. There are two non-flip amplitudes in NN reactions; the general

theory contains no requirement that they behave similarly. At high energies the absence of unnatural parity exchanges apart from the π and B implies these amplitudes are equal. At low energies there is already enough data to see that they are not equal. (This and related phenomena and implications are discussed in Appendix 4.) While the full interpretation of this is not clear, and considerably more data is needed to completely obtain the amplitudes and study such questions, it is already apparent that the extra amplitudes present in NN give the possibility of learning new kinds of physics in this region.

Another aspect of intermediate energies where spin data would be useful is in understanding particle production amplitudes and relating them to the elastic amplitudes. Basically this is a matter of understanding the way unitarity acts and how it modifies hadron amplitudes. It could be that such insights are essential in obtaining an understanding of the hadron spectrum. These are areas where very little work of any sort has been done; experimental data and the discovery of a few systematic regularities would likely stimulate a significant increase in theoretical understanding.

Because of the lack of resonant behavior, the pp system may be a particularly useful place to study the dynamics associated with thresholds and with particle production. In other reactions the strong resonance structure could obscure and interfere with the effects directly due to unitarity.

Quasi-two-body Scattering (Appendices 5 and 6)

The panel feels that diffractive (allowed vacuum exchange) and non-diffractive two-body resonance production are important areas that must be investigated. A consistent and complete theoretical understanding of the Pomeron has escaped theorists. Assuming one can isolate the Pomeron by judicious choice of experiments, questions to ask are: Is inelastic diffraction just a manifestation of the Deck effect or are genuine N^* states produced? If N^* 's are produced, what

are their production properties (e.g. Morrison's rule)? How are the helicity amplitudes for inelastic reactions different from elastic reactions? Does factorization work (e.g. by comparing the nucleon vertex for elastic and inelastic diffraction)?

More specifically, for low mass diffraction dissociation reactions polarization measurements may be of considerable value in illuminating the physical differences between elastic and inelastic diffraction. The latter is expected to be peripheral in impact parameter, and it is thought that diffractive helicity-flip amplitudes are not small. The spin observables will help decide the validity of both of these views.

There are many particle-like states, with names, such as A_1 , A_3 , Q , $N^*(1470)$, etc. Their interpretation remains in doubt. They are produced mainly (or only) near threshold in diffractive reactions. The main differences between interpretations concerns the phases of the production amplitudes, not the shape, and perhaps not the size. Studying such effects in the various low multiplicity final states with polarization measurements perhaps could settle the question. Studying $pp \rightarrow NN^*$ might settle the question for $N^*(1470)$ and clarify it for all states.

Non-diffractive processes allow us to study amplitudes with non-vacuum t-channel quantum numbers in the absence of the Pomeron. This can supplement information obtained in elastic scattering and can allow the study of amplitudes not present in elastic reactions.

In the 1 to 4 GeV/c range, a small number of exclusive low multiplicity channels ($pn\pi^+$, $pp\pi^+\pi^-$) provide large cross-section. Understanding the physics of these reactions is essential for understanding the behavior of σ_{tot} and σ_{el} in the same momentum range. We urge a systematic study of these processes with a polarized beam, with a large solid angle detector.

Inclusive Small t - Region (Appendices 7 and 8)

Polarization studies are important in developing and refining our theoretical understanding of inclusive processes. In particular one learns about such things as triple-Regge interference terms, absorption effects, and factorization of the Reggeon particle scattering amplitude. It is clear that polarization measurements here should provide an impact similar to that produced when two-body polarizations were first detected. However, the triple-Regge region is only a small portion of phase space ($|x| \geq 0.8$, $M^2 > 4 \text{ (GeV/c)}^2$, $0 \leq |t| \leq 1.5 \text{ (GeV/c)}^2$) not easily accessible at Argonne. The M^2 restriction may be relaxed by the use of finite-mass sum rules (see Appendix 8), however, Argonne energies are still not sufficient for a straightforward application of the triple-Regge formalism. On the other hand the polarized beam provides opportunities not found elsewhere. We recommend 5-10% of the polarized beam program be allocated to inclusive studies and that the experiments be carried out at 12.0 GeV/c rather than 6.0 GeV/c. In addition, we feel that meson exchange processes (like $pp \rightarrow pX$ and $pp \rightarrow \Delta^{++}X$) are much more amenable to theoretical interpretation than baryon exchange processes (like $pp \rightarrow \pi X$) and thus should be emphasized. The exclusive breakdown of the inclusive cross-section is an area in which Argonne can excel.

New Unexplored Areas (Large p_T Etc.)

In recent years much theoretical and experimental effort has been devoted to large t two-body exclusive and large p_T inclusive processes. The hope is that the physics at "small distances" might be more fundamental. By probing the hadron one might detect interactions among the basic constituents of matter (possibly quarks). In the opinion of the panel the Argonne polarized beam facility can play a role in this area in the 8 - 12 GeV/c region.

Present day constituent models have not been concerned with polarization

or spin effects. Simple gluon exchange models predict zero polarization, since all amplitudes have the same phase. Nevertheless, in elastic scattering for example, if helicity flip amplitudes are non-zero then there could be differences between transversity cross sections $d\sigma(\uparrow\uparrow)/dt$, $d\sigma(\uparrow\downarrow)/dt$, and $d\sigma(\downarrow\downarrow)/dt$, even if all amplitudes are in phase. It is also of great interest to study the connection between the small t exclusive (small p_T inclusive) region that is described by Regge (triple-Regge) exchanges and the large t (large p_T) constituent scattering region. The constituent interchange model (CIM) predicts that the various Regge trajectory functions $\alpha_i(t)$ become constant (negative integers) at large negative t values (i.e. cross sections fall like a power of s at fixed t). Such behavior could lead to large polarization effects. Consider, for example, πN elastic scattering where the f (and P) Regge exchange couples predominantly to the helicity non-flip amplitude and the ρ Regge exchange couples predominantly to the helicity flip amplitude. The CIM model predicts that the trajectories for this process approach -1 as $-t$ becomes large. The phase-energy relation (Phragmon-Lindeloff theorem) then implies that the f (and P) amplitude has phase $e^{i\pi}$ and that the ρ amplitude has phase $ie^{i\pi}$, which results in maximal polarization (the two amplitudes are 90° out of phase)! In any case the behavior of the polarization as the momentum transfer is increased bears directly on the connection between Regge exchange and constituent scattering. Similarly polarization studies at large p_T in inclusive processes could affect our ideas about the constituent nature of hadrons.

Polarization studies at intermediate t values (i.e. $|t| \geq 1.5 \text{ (GeV/c)}^2$) might be useful in revealing the nature of the basic diffractive part of elastic scattering, called the "Pomeron". If, for example, the Pomeron is a geometric-like object with several diffractive minima then such structure could not be detected in $d\sigma/dt$ at 6.0 or 12.0 GeV/c due to the overwhelming presence of the t -channel exchange forces due to the ρ , A_2 , f , π , etc. On the other hand,

since the polarization is given roughly by the Pomeron interfering with the Regge exchange contributions, one might expect to see considerable structure in this observable at large t . This is the case for pp elastic scattering. Further data on pp elastic scattering and comparisons with np elastic scattering at large t would be very useful in illuminating the obscure "Pomeron".

We have allotted a sizeable fraction (15-25%) of time to these new and relatively unexplored but exciting areas, with a small fraction to go into P and T violation tests. A brief summary of the state of P and T violation tests is given in Appendix 2 of this report. Expected violations in hadron reactions at the level of the weak interaction are at the borderline of experimental feasibility, (e.g., parity violations in π_{TOT}^+ or in inclusive production experiments). A violation at the strong interaction level would have profound consequences. A wide range of experiments have shown no indication of any such violation. Even at ZGS energies and momentum transfers of $\sim \frac{1}{2}$ (GeV/c)² effects in the $\sim 10\%$ range could have been detected. Experiments which have considerably improved accuracy, or go to higher momentum transfers, may find an effect, but must be considered long shots.

Often the behavior of hadrons is said to be complicated. Some of that complexity is the consequence of having many amplitudes present because particles have different spin states and different quantum numbers. Past work and some theoretical ideas suggest that very simple behavior and regularities appear if the individual spin and quantum number amplitudes can be separated out. The polarized beam facility can be an essential and powerful tool in this process; perhaps it will help lead to considerable simplifications in our view of hadron interactions.

III. DETAILED APPENDICES

Summary of Measurements of the Spin Dependence
in NN Interactions from 2 to 12 GeV/c

D. R. Rust

Status of experimental results June 1975. Not a compilation. Older data has been left out if it has been superseded by more accurate or more complete measurements.

I. Polarization

A. $pp \rightarrow pp$

2.50 to 5.15 GeV/c Table 1 and Figure 1
J. H. Parry et al. Phys. Rev. D8 45 (1973)

5.15 GeV/c Table 2 and Figure 2
G. W. Abshire et al. Phys. Rev. Letters 32 1261 (1974)

6.0 GeV/c Table 3 and Figure 3
M. Borghini et al. Phys. Letters 31B 405 (1970)

6.0 GeV/c Table 4 and Figure 4
D. R. Rust et al. to be published E-364

7.0 GeV/c Table 5 and Figure 5
G. W. Abshire et al. Phys. Rev. Letters 32 1261 (1974)

10.0 GeV/c Table 6 and Figure 6
M. Borghini et al. Phys. Letters 36B 501 (1971)

12.3 GeV/c Table 7 and Figure 7
G. W. Bryant et al. to be published E-377

B. $pn \rightarrow pn$

2,3,4,6 GeV/c Table 8 and Figure 8
R. Diebold et al. Phys. Rev. Letters 35 632 (1975)

C. $np \rightarrow pn$

2 - 12 GeV/c Fig. 9
M. A. Abolins et al. Phys. Rev. Letters 30 1183 (1973)

D. $\bar{p}p \rightarrow \bar{p}p$

6 GeV/c Table 9 and Figure 10
M. Borghini et al. Phys. Letters 31B 405 (1970)

E. $\bar{p}p \rightarrow \pi\pi$

Table 10 and Figure 11
P. LeDu et al. Phys. Letters 44B 390 (1973)

II. Other spin parameters in pp elastic scattering

A. R. parameter 6 GeV/c Table 10 and Figure 12
J. DeRegel et al. Phys. Letters 43B 338 (1973)

B. C_{nn}

3 GeV/c Figure 13 E-372

4 GeV/c Figure 14 E-372

6 GeV/c Table 11 and Figure 15
G. Hicks et al. to be published E-372

6 GeV/c Table 12 and Figure 16
R. C. Fernow et al. Phys. Letters 52B 243 (1974)

C. D_{nn}

3,6 GeV/c Table 13 and Figure 17
G. W. Abshire et al. to be published E-189

6 GeV/c R. C. Fernow et al. Phys. Letters 52B 243 (1974)
1 point plotted in Fig. 17

D. K_{nn}

6 GeV/c R. C. Fernow et al. Phys. Letters 52B 243 (1974)
1 point at $P_{\perp}^2 = .5 \text{ (GeV/c)}^2$: $K_{nn} = .14 \pm .08$

E. (S, N; O, S) E-385 no results yet

III. Other Measurements

A. $pp \rightarrow pp$ Polarized total cross-section
2-6 GeV/c Fig. 18
W. DeBoer et al. Phys. Rev. Letters 34 558 (1975)

B. Inclusive reactions

1. $p \rightarrow pX$ E-364 Fig. 19 Diebold Group

2. $p \rightarrow p \pi X$ Fig. 20

D. Aschaan et al. London Conf.

50116

- C. Δ production with polarized beam E-339
 A. Wicklund Results too extensive for this compilation
- D. Λ production with polarized beam E-336
 R. Winston - T. Romanowski
 Argonne Preprint ANL-HEP-PR-75-24 Figure 21
- E. Parity Violation D. Nagle E-354: results consistent with $\Lambda \rightarrow p n^-$
- F. Polarized beam in 12 ft. chamber D. Robineon E-367
 (to be done soon)

$pp \rightarrow pp$ J.H. Pary et al.
 Phys. Rev. D8 45 (1973)

FIGURE 1a

TABLE I. Measured values of the polarization in elastic proton-proton scattering.

Minimum (GeV/c)	$-t$ (GeV ² /c ²)	Polarization	Error	Maximum (GeV/c)	$-t$ (GeV ² /c ²)	Polarization	Error
2.59	0.233	0.482	0.021	3.75	0.259	0.259	0.009
	0.245	0.293	0.021		0.277	0.277	0.009
	0.251	0.269	0.021		0.291	0.291	0.009
	0.278	0.282	0.015		0.309	0.309	0.009
	0.283	0.279	0.016		0.323	0.323	0.010
	0.301	0.297	0.017		0.339	0.339	0.010
	0.331	0.297	0.020		0.362	0.362	0.011
	0.358	0.225	0.029		0.389	0.389	0.012
	0.393	0.228	0.013		0.402	0.402	0.012
	0.432	0.130	0.013		0.421	0.421	0.014
	0.462	0.130	0.014		0.442	0.442	0.014
	0.513	0.128	0.017		0.463	0.463	0.015
2.75	0.701	0.209	0.028	3.75	0.484	0.484	0.016
	0.769	0.094	0.020		0.504	0.504	0.016
	0.877	0.045	0.022		0.525	0.525	0.016
	0.889	0.049	0.022		0.548	0.548	0.016
	1.094	0.038	0.021		0.571	0.571	0.016
	0.245	0.276	0.016		0.595	0.595	0.016
	0.258	0.275	0.015		0.612	0.612	0.016
	0.280	0.255	0.011		0.627	0.627	0.016
	0.310	0.263	0.012		0.679	0.679	0.016
	0.338	0.251	0.013		0.716	0.716	0.016
	0.367	0.233	0.014		0.847	0.847	0.016
	0.388	0.230	0.015		0.858	0.858	0.016
2.93	0.422	0.225	0.017	3.75	1.048	1.048	0.016
	0.442	0.215	0.017		1.056	1.056	0.016
	0.455	0.155	0.015		1.132	1.132	0.016
	0.569	0.122	0.016		1.216	1.216	0.016
	0.768	0.106	0.017		1.255	1.255	0.016
	0.807	0.092	0.019		1.422	1.422	0.016
	0.976	0.109	0.021		1.444	1.444	0.016
	1.076	0.077	0.024		1.531	1.531	0.016
	1.178	0.071	0.029		1.795	1.795	0.016
	1.328	0.057	0.013		1.848	1.848	0.016
	0.232	0.242	0.015		2.053	2.053	0.016
	0.245	0.217	0.013		2.206	2.206	0.016
3.25	0.260	0.236	0.014	3.75	2.241	2.241	0.016
	0.284	0.231	0.009		2.464	2.464	0.016
	0.316	0.225	0.011		2.486	2.486	0.016
	0.338	0.207	0.011		2.506	2.506	0.016
	0.378	0.202	0.011		0.258	0.258	0.009
	0.415	0.222	0.011		0.295	0.295	0.009
	0.459	0.180	0.015		0.334	0.334	0.009
	0.487	0.177	0.017		0.377	0.377	0.009
	0.527	0.158	0.021		0.423	0.423	0.009
	0.592	0.152	0.013		0.472	0.472	0.010
	0.722	0.132	0.014		0.513	0.513	0.010
	0.829	0.116	0.016		0.544	0.544	0.010
3.25	0.918	0.116	0.017	3.75	0.575	0.575	0.010
	1.018	0.116	0.017		0.615	0.615	0.010
	1.112	0.081	0.020		0.675	0.675	0.010
	1.256	0.091	0.021		0.722	0.722	0.010
	1.443	0.099	0.019		0.783	0.783	0.010
	0.232	0.232	0.009		0.862	0.862	0.010
	0.242	0.221	0.009		0.913	0.913	0.010
	0.260	0.229	0.009		1.000	1.000	0.010
	0.282	0.221	0.009		1.236	1.236	0.010
	0.310	0.211	0.009		1.404	1.404	0.010
	0.338	0.203	0.009		1.568	1.568	0.010
	0.367	0.195	0.009		1.748	1.748	0.010

PP → PP J. H. Parry et al.
Phys. Rev. D 8 45 (1973)

FIGURE 1b

TABLE 1. (Continued)

Momentum (GeV/c)	$\sqrt{s}$ (GeV/c) ²	Polarization	Error	Momentum (GeV/c)	$\sqrt{s}$ (GeV/c) ²	Polarization	Error
	1.910	0.218	0.037		1.869	0.145	0.052
	2.061	0.168	0.042		2.038	0.107	0.070
	2.298	0.122	0.043		2.277	-0.019	0.092
					2.509	0.181	0.129
4.40	0.233	0.167	0.013		2.710	0.010	0.135
	0.255	0.156	0.013		2.860	0.022	0.111
	0.278	0.185	0.014				
	0.301	0.152	0.013	5.15	0.341	0.148	0.011
	0.326	0.155	0.014		0.411	0.141	0.013
	0.351	0.152	0.015		0.488	0.137	0.015
	0.377	0.150	0.016		0.565	0.090	0.018
	0.402	0.152	0.017		0.625	0.077	0.034
	0.431	0.149	0.018		0.670	0.064	0.029
	0.459	0.153	0.020		0.736	0.085	0.027
	0.485	0.127	0.020		0.825	0.085	0.035
	0.517	0.115	0.022		0.916	0.098	0.043
	0.549	0.125	0.024		1.021	0.147	0.053
	0.579	0.116	0.028		1.124	0.198	0.065
	0.624	0.126	0.020		1.232	0.145	0.066
	0.695	0.085	0.024		1.349	0.131	0.080
	0.765	0.075	0.030		1.451	-0.145	0.100
	0.838	0.102	0.034		1.574	0.069	0.110
	0.905	0.075	0.040		1.749	0.221	0.104
	0.955	0.052	0.044		2.234	0.331	0.112
	1.051	0.116	0.050		2.800	0.128	0.154
	1.157	0.183	0.053		3.333	0.131	0.145
	1.445	0.158	0.037		3.735	-0.031	0.275
	1.627	0.178	0.043		4.055	-0.214	0.279

J. H. Parry et al.
Phys. Rev. D8 45 (1973)

Figure 2

G.W. Abshire et al
Phys. Rev. Lett. 32 1261 (1974)

Table 2

Lab Momentum -- 5.15 GeV/c	$\sqrt{s}$ (GeV/c) ²	Polarization	Error
	1.941	-0.111	± 0.318
	2.061	0.076	± 0.311
	2.181	-0.101	± 0.321
	2.301	-0.167	± 0.327
	2.421	-0.142	± 0.321
	2.541	-0.198	± 0.324
	2.661	-0.218	± 0.312
	2.781	-0.163	± 0.313
	2.901	-0.260	± 0.330
	3.021	-0.278	± 0.324
	3.141	-0.256	± 0.316
	3.261	-0.252	± 0.319
	3.381	-0.277	± 0.311
	3.501	-0.271	± 0.321
	3.621	-0.284	± 0.328

Polarization parameter P_0 in pp elastic scattering at 5 GeV/c

$ t $ (GeV/c) ²	P_0
0.075 ± 0.025	0.104 ± 0.032
0.125 ± 0.025	0.122 ± 0.044
0.175 ± 0.025	0.137 ± 0.067
0.225 ± 0.025	0.131 ± 0.067
0.275 ± 0.025	0.142 ± 0.099
0.325 ± 0.025	0.112 ± 0.099
0.375 ± 0.025	0.124 ± 0.041
0.425 ± 0.025	0.113 ± 0.043
0.475 ± 0.025	0.099 ± 0.015
0.525 ± 0.025	0.099 ± 0.017
0.575 ± 0.025	0.032 ± 0.019
0.625 ± 0.025	0.112 ± 0.020
0.675 ± 0.025	0.107 ± 0.019
0.725 ± 0.025	0.097 ± 0.040
0.775 ± 0.025	0.107 ± 0.037
0.825 ± 0.025	0.094 ± 0.042
0.875 ± 0.025	0.007 ± 0.045
0.925 ± 0.025	0.001 ± 0.056
0.975 ± 0.025	0.160 ± 0.056
1.05 ± 0.03	0.131 ± 0.022
1.15 ± 0.03	0.217 ± 0.013
1.25 ± 0.03	0.244 ± 0.013
1.40 ± 0.10	0.155 ± 0.059
1.60 ± 0.10	0.074 ± 0.029
1.80 ± 0.10	0.120 ± 0.127
2.00 ± 0.10	0.058 ± 0.102
2.30 ± 0.20	0.060 ± 0.052

Table 3

Fig. 3

PP → PP

M. Borghini et al.
Phys. Letters 31B 405 (1970)

PP → PP 6 GeV/c

D.R. Rust et al.

Table 4

E-364

$-t$ (GeV ²)	P	ΔP
.03	.085	± .021
.05	.100	.009
.07	.120	.009
.09	.119	.010
.11	.122	.010
.13	.117	.011
.15	.130	.012
.17	.157	.013
.19	.145	.014
.22	.129	.011
.26	.144	.013
.30	.111	.016
.34	.109	.018
.38	.148	.021
.42	.140	.025
.46	.072	.029

Fig. 4

G.W. Abshire et al.
Phys. Rev. Letters 32 1261 (1974)

Table 5

Lab momentum -- 7.00 GeV/c

$-t$ (GeV/c) ²	Polarization	Error
.162	.079	±.019
.473	.078	±.025
.770	.046	±.022
.893	-.1	±.024
1.040	.079	±.035
1.357	.141	±.025
1.364	.189	±.030
1.476	.126	±.018
1.643	.201	±.022
2.053	.181	±.030
2.288	.127	±.038
2.450	.167	±.031
2.617	.181	±.020
2.873	.083	±.029
3.318	.042	±.037
3.781	.080	±.036
5.245	-.044	±.059

G.W. Bryant et al. Indiana
E-377
Table 7

Polarization in p-p Elastic Scattering at 12.3 GeV/c

θ_{CM}	$ t $	P	ΔP
31.0°	1.531	.147	.020
33.0°	1.730	.175	.032
35.0°	1.939	.119	.023
37.0°	2.159	.071	.020
38.5°	2.331	.015	.062
40.0°	2.508	.052	.029
41.0°	2.630	.048	.060
42.0°	2.754	.062	.028
43.5°	2.945	.094	.038
45.0°	3.140	.034	.031
50.0°	3.830	-.007	.083
55.0°	4.572	-.092	.116
60.0°	5.361	.086	.117
65.0°	6.191	.033	.080

10 GeV/c

$ t $ (GeV/c) ²	P_0 (%)
0.10 ± 0.02	9.1 ± 1.1
0.14 ± 0.02	8.5 ± 0.6
0.18 ± 0.02	8.9 ± 0.9
0.22 ± 0.02	8.1 ± 0.8
0.26 ± 0.02	8.0 ± 0.7
0.30 ± 0.02	4.0 ± 1.2
0.34 ± 0.02	5.9 ± 1.3
0.38 ± 0.02	4.9 ± 1.4
0.42 ± 0.02	6.2 ± 1.5
0.46 ± 0.02	5.5 ± 1.8
0.48 ± 0.03	6.7 ± 1.2
0.53 ± 0.03	5.1 ± 1.1
0.61 ± 0.03	4.2 ± 1.2
0.67 ± 0.03	4.5 ± 1.5
0.73 ± 0.03	2.5 ± 2.2
0.79 ± 0.03	0.7 ± 2.0
0.85 ± 0.03	0.9 ± 2.0
0.91 ± 0.03	0.2 ± 2.3
0.97 ± 0.03	0.3 ± 3.0
1.03 ± 0.03	2.3 ± 3.8
1.09 ± 0.03	4.0 ± 4.0
1.15 ± 0.06	6.5 ± 3.5
1.20 ± 0.06	14.0 ± 3.5
1.42 ± 0.05	15.0 ± 4.0
1.54 ± 0.06	21.0 ± 4.3
1.66 ± 0.06	17.0 ± 6.0
1.78 ± 0.06	9.5 ± 5.5
1.89 ± 0.06	2.0 ± 3.5
2.05 ± 0.12	3.0 ± 4.5
2.20 ± 0.12	7.0 ± 3.5
2.54 ± 0.12	4.0 ± 7.0
2.78 ± 0.12	4.0 ± 11.0

Table 6

PP → PP
M. Borghini et al.
Phys. Letters 36B 501 (1971)

TABLE 1. Polarization asymmetry in percent for pp and pn elastic scattering for 2- to 6-GeV/c incident beam momentum. Errors shown are statistical only.

$-t$ GeV ²	2 GeV/c		3 GeV/c		4 GeV/c		6 GeV/c	
	P(pp)	P(pn)	P(pp)	P(pn)	P(pp)	P(pn)	P(pp)	P(pn)
0.15	34.4 ± 1.7	20.4 ± 1.5	23.6 ± 1.8	13.8 ± 1.4	19.0 ± 1.6	7.0 ± 1.2	13.0 ± 1.0	1.1 ± 1.5
0.17	40.0 ± 1.7	26.7 ± 1.6	24.5 ± 1.8	12.7 ± 1.5	18.3 ± 1.7	8.1 ± 1.3	11.2 ± 1.1	2.4 ± 1.5
0.19	36.7 ± 1.8	25.2 ± 1.7	28.6 ± 1.9	13.7 ± 1.6	14.3 ± 1.8	7.3 ± 1.4	11.5 ± 1.2	2.2 ± 1.6
0.22	36.9 ± 1.0	31.5 ± 0.8	26.0 ± 1.4	13.2 ± 1.3	18.8 ± 1.1	8.3 ± 0.6	10.2 ± 1.0	3.2 ± 0.8
0.26	36.8 ± 0.9	28.8 ± 0.8	25.2 ± 1.3	13.4 ± 1.1	19.3 ± 1.2	9.7 ± 0.9	12.3 ± 1.1	3.0 ± 0.8
0.30	36.4 ± 1.1	28.9 ± 0.9	25.6 ± 1.1	12.4 ± 0.9	19.0 ± 1.2	9.2 ± 0.9	11.1 ± 1.2	3.3 ± 0.9
0.34	34.5 ± 1.5	26.6 ± 1.3	29.0 ± 1.1	12.9 ± 0.9	20.5 ± 1.3	9.5 ± 0.9	12.2 ± 1.3	3.3 ± 1.0
0.38	30.3 ± 2.1	24.0 ± 1.7	25.7 ± 1.2	11.3 ± 1.0	17.8 ± 1.5	8.6 ± 1.1	13.9 ± 1.5	3.0 ± 1.2
0.45	31.1 ± 1.7	20.9 ± 1.4	24.4 ± 0.9	11.7 ± 0.7	17.2 ± 1.2	8.3 ± 0.7	11.8 ± 1.1	1.2 ± 0.8
0.55	23.1 ± 2.3	15.6 ± 1.9	20.0 ± 1.3	10.0 ± 1.0	15.1 ± 1.6	5.8 ± 1.1	8.9 ± 1.2	-0.7 ± 0.9
0.65	17.5 ± 3.3	12.6 ± 2.6	17.9 ± 1.8	3.8 ± 1.3	13.3 ± 2.2	3.7 ± 1.5	6.5 ± 1.6	-1.4 ± 1.2
0.75	6.8 ± 8.4	10.2 ± 5.6	13.8 ± 2.6	1.0 ± 1.8	11.9 ± 3.0	-3.0 ± 1.9	7.3 ± 2.2	-3.7 ± 1.5
0.90	-	-	13.7 ± 3.3	-0.2 ± 2.3	16.9 ± 3.4	-3.7 ± 2.1	12.8 ± 2.2	-6.4 ± 1.6
1.10	-	-	6.1 ± 7.1	-10.1 ± 3.9	9.6 ± 8.6	-7.8 ± 4.4	11.1 ± 3.6	-5.3 ± 2.4
1.30	-	-	-	-	-	-	19.0 ± 6.3	2.2 ± 3.9
1.50	-	-	-	-	-	-	22.8 ± 11.4	-1.6 ± 9.8

Table 8

$pn \rightarrow pn$

Figure 8
R. Diebold et al.
Phys. Rev. Letters
35 632 (1975)

FIG. 1. Polarization asymmetries for pp and pn elastic scattering at four incident momenta. The errors are statistical only and do not include the $\pm 6^\circ$ scale uncertainty from the beam polarization. Fits to the data from 0.15 to 1.0 GeV² using Eq. (13) are shown as bands (± 1 standard deviation).

FIG. 9. Polarization parameter for five laboratory-momentum bins. Data of Ref. 7 shown for comparison.

Fig. 9

$n\bar{p} \rightarrow p\bar{n}$

M. A. Abolins et al.

Phys. Rev. Letters 30 1183 (1973)

[normal to scattering plane defined as $k_n^{in} \times k_n^{out}$]

Table 10

Polarization parameter $P(t)$ for the reaction $\bar{p}p \rightarrow \bar{n}n$ at 8 GeV/c.

$-t$ intervals (GeV/c) ²	$P(t)$
0.00 - 0.05	0.00 ± 0.06
0.05 - 0.15	-0.13 ± 0.05
0.15 - 0.25	-0.16 ± 0.05
0.25 - 0.35	-0.22 ± 0.09
0.35 - 0.45	-0.18 ± 0.12
0.45 - 0.55	-0.08 ± 0.16
0.55 - 0.80	-0.40 ± 0.24

$\bar{p}p \rightarrow \bar{n}n$

P. Le Du et al.

Phys. Letters 44B 390 (1973)

Fig. 2. (a) Differential cross-section $\bar{p}p \rightarrow \bar{n}n$ at 8 GeV/c obtained from butanol data. The errors shown are only statistical. The estimated normalization error of $\pm 15\%$ is not included. The solid line is a fit to previous measurements [2]. (b) Polarization parameter $P(t)$ for the reaction $\bar{p}p \rightarrow \bar{n}n$ at 8 GeV/c. Two predictions based on Regge models are also shown: solid curve ref. [6], dashed curve ref. [7].

Figure 11

Table 9

Polarization parameter P_0 in $\bar{p}p$ elastic scattering at 6 GeV/c

t (GeV/c) ²	P_0
0.10 ± 0.03	0.108 ± 0.074
0.20 ± 0.05	0.119 ± 0.052
0.325 ± 0.275	0.6 ± 0.127

$\bar{p}p \rightarrow \bar{p}p$

M. Bognini et al., Phys. Letters 31B 405 (1970)

Figure 10

E-372 PRELIMINARY

Figure 12

R parameter 6 GeV/c

J. DeRegel et al

Phys. Letters 43B 338 (1973)

Table 11

Spin rotation parameter $C = 0.999 R + 0.052 A$ in proton-proton elastic scattering

Incident Momentum GeV/c	$\sin^2 \theta$ (GeV/c) ²	$C \pm C \pm \Delta C$	
		Mean Value	Interval
6.0	± 0.13	0.227	0.180 - 0.252
		0.269	0.252 - 0.286
		0.303	0.286 - 0.320
		0.336	0.320 - 0.354
		0.370	0.354 - 0.388
		0.418	0.388 - 0.456
		0.492	0.456 - 0.540
			-0.17 + 0.24
			-0.19 + 0.21
			-0.42 + 0.20
			-0.56 + 0.20
			-0.55 + 0.20
			-0.06 + 0.16
			-0.16 + 0.21

E-372 PRELIMINARY

Table II

C_{NN} at 6 GeV/c	C_{NN}	ΔC_{NN}
0.10	0.049	0.076
0.17	0.041	0.021
0.27	0.111	0.019
0.38	0.129	0.033
0.51	0.131	0.038
0.66	0.152	0.052
0.82	0.128	0.066
0.99	0.073	0.085
1.18	-0.024	0.118
1.38	0.083	0.131

$|t|$

0.10
0.17
0.27
0.38
0.51
0.66
0.82
0.99
1.18
1.38

Figure 16

Fig. 2. The quantity $\frac{\sum A_{ij}^2}{\sum C_{ij}^2}$ as a function of P^2 for pp elastic scattering at 6.0 GeV/c.

R.C. Fernow et al.
Phys. Letters 52B 243 (1974)

Table 13

$\sqrt{s}$ (GeV/c) ²	$\frac{A(11)}{C(00)}$	$\frac{A(11)}{C(00) + C(02)}$	$\frac{A(11)}{C(00) + C(02)}$	A	C_{nn}
0.53	1.385 ± 0.005	0.907 ± 0.003	0.893 ± 0.005	0.101 ± 0.002	0.092 ± 0.003
0.84	1.283 ± 0.010	0.883 ± 0.005	0.931 ± 0.010	0.082 ± 0.004	0.117 ± 0.005
0.76	1.272 ± 0.012	0.890 ± 0.005	0.918 ± 0.012	0.081 ± 0.005	0.110 ± 0.006
0.88	1.246 ± 0.016	0.700 ± 0.010	0.934 ± 0.016	0.078 ± 0.007	0.090 ± 0.010
1.00	1.313 ± 0.035	0.925 ± 0.014	0.917 ± 0.035	0.119 ± 0.010	0.074 ± 0.014
1.13	1.306 ± 0.032	0.970 ± 0.018	0.754 ± 0.032	0.128 ± 0.021	0.070 ± 0.018
1.15	1.321 ± 0.030	0.957 ± 0.016	0.765 ± 0.030	0.130 ± 0.012	0.043 ± 0.016
1.47	1.426 ± 0.034	0.942 ± 0.019	0.700 ± 0.034	0.184 ± 0.014	0.058 ± 0.019
1.83	1.363 ± 0.036	0.985 ± 0.020	0.677 ± 0.036	0.169 ± 0.015	0.039 ± 0.020
2.10	1.244 ± 0.042	1.008 ± 0.015	0.740 ± 0.042	0.126 ± 0.025	-0.008 ± 0.015
2.81	1.301 ± 0.055	0.985 ± 0.030	0.719 ± 0.055	0.140 ± 0.023	0.015 ± 0.030

Figure 15

Figure 17

Table 14

Values of the Depolarization Parameter in
Proton-Proton Elastic Scattering

P_{LAB} (GeV/c)	θ_{cm} (deg.)	$-t(\text{GeV}/c)^2$	D	ΔD
3.0	30	0.277	0.946	.136
3.0	40	0.484	1.058	.071
3.0	50	0.739	0.909	.128
6.0	20	0.291	0.910	.113
6.0	25	0.451	1.040	.082
6.0	30	0.645	1.003	.047
6.0	35	0.871	0.739	.170
6.0	40	1.127	0.874	.148
6.0	45	1.411	0.533	.291
6.0	50	1.721	0.404	.184

FIG. 1. The difference between the proton-proton total cross sections in the antiparallel and parallel spin states plotted against the incident beam momentum. The spins are measured perpendicular to the beam direction. The normal (spin-averaged) σ_{tot} taken from other experiments (Ref. 5) is also shown. The data are preliminary but the final values should fall within the quoted error bars.

Fig. 18 Polarized total cross-section
W. DeBoer et al. Phys. Rev. Letters 34 558 (1975)

Figure 19

Figure 20

TIME REVERSAL AND PARITY TESTS

K. Terwilliger

University of Michigan

Ann Arbor 48104

A recent review by Henley¹ discusses the present status of Time Reversal and Parity symmetry violations, and comments on the implications for high energy hadron scattering. This note will briefly summarize the situation with particular attention to the sizes of possible effects, relating them to experimental accuracy available or reasonably possible at the ZGS.

Time Reversal

The level of the TR violating interaction relative to the strong interaction which is implied by CP non-conservation in K_2^0 decay is $\sim 2 \times 10^{-3} \times_{\text{weak}} (10^{-6}) \sim 10^{-9}$, clearly not testable in scattering experiments. The most sensitive test for TR violation (also requiring a parity violation available via the weak interaction) is the electric dipole moment of the neutron, presently measured to be less than 10^{-23} e-cm, nearing the range where the effect is predicted by milliweak theories (10^{-23} - 10^{-24}) still far from the superweak (10^{-27}). Presumably any strong or electromagnetic effects would have shown up at a lower level and must be considered highly unlikely candidates for the basic cause of the violation.

Experimental tests of TR in hadronic reactions are much less sensitive--presently testing at 3×10^{-3} of hadronic (example: a 20 MeV nuclear detailed balance experiment agrees with TR invariance with accuracy of .3%). A higher energy (300-700 MeV) test involving a gamma, $np \rightarrow \gamma d$ is consistent with TR invariance at the few percent level.

A direct test of TR invariance in nucleon-nucleon elastic scattering is the comparison of the polarization parameter (P) with asymmetry parameter (A). (Experimenters usually equate A with P using TR invariance, calling it a single parameter P). P experiments require a polarization measurement via a secondary scattering, A experiments measure intensity changes as the beam or target polarization is varied. Some experimental data using the two techniques, hence comparing P and A, are shown in Fig. 1. Experimental accuracy is typically a few percent. In general, the agreement of the P and A measurements is reasonably good, even up to GeV energies and momentum transfers.

On the theoretical side, a strong TR violating model of Sudarshan was used by Binstock, Bryan and Gersten to estimate possible P-A difference in pp and np elastic scattering. At 425 MeV they obtained up to .04 for pp, up to .2 for np -- the np system is clearly more sensitive for their model. Some P-A np data exists at 600 MeV, and shows a possible 10% difference. Another two spin elastic test of TR was also calculated, with results of approximately the same size as P-A.

At the ZGS, P-A measurements can be made to at least the level of accuracy indicated in Fig. 1. For substantial runs, accuracy of .01 for A, .02 for P should be obtainable at $P_A \sim 1$.

Parity

Parity violations are observed in weak interactions at the full strength of the weak interaction -- 10^{-6} of hadronic. Parity violations occur in hadronic reactions at a level expected from weak interaction effects, as in the capture of thermal neutrons by protons, $np \rightarrow \gamma d$, where a circular polarization of the γ is observed at the level of 10^{-6} . Similarly small parity violating effects are expected in measurements of the dependence of total pp cross sections on the helicity of the incoming proton. Measurements at 15 MeV showed no effects at a level of 4×10^{-7} (pp) nor did a 6 GeV/c p-Be experiment at the 10^{-5} level -- both measurements still somewhat above the predicted range. Another indication of the small level of parity violation in hadronic interactions is the lack of any observations of longitudinal polarization in λ^0 decay, where effects of more than a few percent should have been noticed.

The appearance of parity violation only at the weak level points to its being a purely weak effect. If so, due to the short range of the weak interaction, parity violating effects in hadronic reactions can probably be most readily observed at large momentum transfers. Henley, assuming an inclusive hadronic cross section dependence of P_A^{-8} , estimates equality of strong and weak amplitudes at $\sim P_A = 17$ GeV/c. If the process is an interference between weak and strong amplitudes, the relative parity violating effect in inclusive reactions might be $\sim (P_A/17)^4$, or 10^{-4} at $P_A = 1.7$ GeV/c. Even with this relatively large rate, the difficulty

in going down to the weak level at the ZG is clear -- $\sim 10^8$ events are required for an accuracy of 10^{-4} . It also has been pointed out that as the weak level is approached inclusive reactions, which contain secondaries from parity violating weak decays, may prove difficult to interpret. In elastic scattering, the similar form factors will probably keep the weak interaction a small fraction of the hadronic even at high momentum transfer.

A ZGS pp elastic three spin experiment presently on the floor measures a parity violating term to an accuracy of $\sim .05$ in the $P_A = 1$ GeV/c range. Measurement of a parity violating asymmetry generated with just a single spin should be possible with an order of magnitude better accuracy.

References

1. E.M. Henley, Argonne National Laboratory Summer Study on Physics with Polarized Beams. July 1974. J.B. Roberts, editor. (And contained references.)
See also, E.M. Henley, Ann. Rev. Nucl. Sci. 19, 367 (1969).

Fig 1.
From H. Akai and M. L.
PR 161 1559 (67)
r-p scattering

P

■

A

○

□

△

■

□

△

■

□

△

■

□

△

A Picture Book of Nucleon-Nucleon Scattering:
Amplitudes, Models, Double- and Triple-spin Observables**

R. D. FIELD and P. R. STEVENS
California Institute of Technology
Pasadena, California 91125

ABSTRACT

We present a comprehensive study of nucleon-nucleon scattering with particular emphasis on the underlying amplitude structure. The five complex NN amplitudes are determined as a function of energy and momentum transfer from existing pp, $\bar{p}p$, and np elastic scattering data and np and $\bar{p}p$ CHFX data. Some constraints determined from meson-baryon fits are imposed. The resulting amplitudes are used to make predictions of forthcoming double- and triple-spin measurements, and are also compared with the model amplitudes of Kane and Seidl. In addition, we discuss the usefulness of transversity amplitudes in NN scattering, examine the status of our present knowledge concerning them, and display model predictions of these amplitudes. The paper is presented in a "picture book" form so that the reader can get a good overview of NN scattering by studying the figures and reading the tables and figure captions.

*Work supported under the auspices of the U. S. Energy Research and Development Administration under Contract No. E(11-1)-68.

**This work is the result of our participation on a Technical Advisory Panel (TAP) for NN scattering at Argonne National Laboratory and will be included as an Appendix of the final report submitted by the panel.

1. Introduction

In recent years much theoretical and experimental effort has shifted from the two-body or quasi-two-body small momentum transfer region to either large- t two-body exclusive or large p_T inclusive processes. There are two primary reasons for this migration. On the one hand there is the hope that the physics at "small distances" might be both simpler and more fundamental; by probing the hadron "deeper" one might indeed be learning about the interactions among the basic constituents (possibly quarks). On the other hand, so much data now exists in the small momentum transfer region and the behavior of this data is so complex that there is a widespread feeling it is just too difficult, if not impossible, to learn anything fundamental from the study of these processes. Furthermore, no existing model can explain all the features of the present data and the more successful ones are so complex that they appear to "describe everything but predict nothing."

Although no fundamental theoretical understanding of small- t scattering exists, progress has nevertheless been made in recent years due to the increasing precision and variety of the experimental data. Thus, for example, even though we cannot "explain" the behavior of an individual reaction, we do know that SU(3) and the naive quark model work quite well in relating one reaction to another^{1,2}. In addition the appropriateness of a t-channel quantum number exchange picture cannot be denied. By taking appropriate combinations of related reactions, it has been possible to isolate amplitudes corresponding to exchanges of specific t-channel quantum numbers. The forces due to π , ρ , and A_2 exchange show great regularities from one process to another. The ρ and A_2 exchanges always couple predominantly to helicity flip amplitudes and show energy dependences related to their trajectory functions $\alpha(t)$. The properties of the π and ω are less well known but they appear to couple predominantly to helicity non-flip amplitudes.

There exists within the t-channel exchange picture several problems that should be pointed out. Regge poles alone are never sufficient to describe a scattering process. Corrections must always be introduced to account for such effects as absorption (Regge cuts and Regge-Regge cuts) and/or lower-lying contributions and there is no convincing way to calculate these correction terms. Also, the precise nature of the Pomeron is not understood, greatly complicating the analysis of diffractive processes. Although the existence of π exchange is established beyond a doubt, a puzzle remains in that its effective trajectory function appears to be quite different from that of other Regge poles³⁾.

Progress in understanding nucleon-nucleon scattering has been particularly slow up till now because this system is so overwhelmingly complicated. First, five independent complex amplitudes are needed at each s and t value to completely specify the observables. Second, these amplitudes may receive contributions from a large number of possible exchanges (i.e. P , f , ω , ρ , A_2 , π , B), including the mysterious Pomeron and the puzzling π and the not-well-known B . To isolate amplitudes of definite t-channel quantum numbers, one must analyze simultaneously pp, $\bar{p}p$, and np elastic scattering and np and $\bar{p}p$ charge exchange (CHEX). However, with the advent of a polarized beam at Argonne and the possibility of making double- and triple-spin measurements, one can hope to make dramatic progress in nucleon-nucleon scattering, which in turn will improve our understanding of two-body scattering amplitudes in general.

A model, developed by G. Kane has been applied to a great many processes and has achieved considerable success. The model is based on Regge poles (R)

and absorptive corrections ($P \times R$) which are calculated according to a definite prescription (the Soper-Volk prescription for calculating box diagram contributions). One aspect of the approach is that one must allow great freedom for the input poles P (they have no WSM and non-LAD type of signature factors).

For those who like the input poles to have some semblance of FPD and duality, this is unpleasant. In addition, inelastic intermediate states play an important role in Kane's Model. These are taken into account by using an effective Pomeron which is quite complicated and turns out to differ significantly from the Pomeron in elastic scattering. This is a feature of the model that makes quantitative predictions difficult since they often depend sensitively on detailed features of the effective Pomeron which cannot be calculated but must be determined from the data. Thus only by applying the model to a great many reactions and checking for consistency of the parameters can the model be tested. In this respect it has been quite successful. It has been able to successfully reproduce most of the features of $PB \rightarrow PB$ ⁴⁾ and $PB \rightarrow \bar{P}B$ ⁵⁾ scattering processes and has recently been applied to nucleon-nucleon scattering⁶⁾. We compare predictions from Kane's model for NN scattering with other possible approaches and find that, although it is not easy, it is possible to distinguish among various models by measuring certain double- and triple-spin observables.

In this paper we present fits to the available nucleon-nucleon scattering data using various model assumptions. While we have not included every datum, we have included all qualitatively different measurements in the momentum range 1-20 GeV/c, and in the t range 0 to -1.4 (GeV/c)² for the reactions for pp, $\bar{p}p$, and np elastic scattering and $\bar{p}p$ and np charge exchange scattering. The observables included in the fits are $d\sigma/dt$, ρ , σ_{tot} , Re/Im , ϵ_{NN} and D_{NN} . Having determined the NN amplitudes as well as possible from existing data, predictions of forthcoming measurements of double- and triple-spin observables are made and their significance discussed.

We take a somewhat different approach from Kane in our fits to NN scattering. We assume that the input Regge poles do indeed have some semblance of FPD and

duality (i.e. they have WSNZ and EXD-type of signature factors). The correction terms are not calculated according to any existing prescriptions but merely determined from the features of the data. Wherever it is sensible to do so, we have constrained our NN amplitudes to be consistent with previous fits to meson-baryon scattering. We have thereby reduced some of the freedom of the NN parameterizations and have at the same time produced a picture of NN scattering which is consistent with the more extensively studied meson-baryon system.

We are not attempting to peddle our parameterizations as a new "model" of high energy scattering. Our correction terms cannot be calculated from any fundamental theory. The amplitudes are parameterized by sums of analytic functions each obeying the phase-energy relation and we have gone to great effort to ensure that they are capable of reproducing the features of the data. In this context our efforts can be considered as a (non-unique) amplitude analysis from the existing data. We must confess, however, that in the back of our minds we consider the pole correction terms as absorptive corrections (Regge cuts or Regge-Regge cuts) which will someday be calculated from a complete theory of high energy scattering.

In Sec. II we discuss various model approaches to NN scattering and in Sec. III examine the double- and triple-spin observables. The usefulness of transversity amplitudes in NN scattering is discussed in Sec. IV together with model predictions as to their nature. Sec. V is reserved for summary and conclusions.

II. The Models

(a) Field-Stevens Amplitude Parameterizations

The ultimate aim of NN scattering measurements is, of course, to completely understand the behavior of the five complex amplitudes that describe the process. Unfortunately the data are not sufficient to provide a "model independent" amplitude determination. One is forced to parameterize the amplitudes and perform a fit to the existing data; a procedure that is not unique. We parameterize the amplitudes in terms of the natural parity Pomeron, f , ω , ρ and A_2 Regge poles and the two unnatural parity π and B Regge poles. To each of these poles we apply a correction term (f_c , ω_c , ρ_c , A_2^c , π_c and B_c) which allows for such effects as Regge cuts (absorption) and/or lower lying poles. These correction terms are not calculated according to any of the existing prescriptions for Regge-cuts but merely determined from features of the data. The input Regge poles ρ and ω contain wrong-signature zeros (WSNZ) and the signature factors are taken to be of the exchange degenerate (EXD) type

$$\xi^\tau(x) = (1 + e^{-i\pi\alpha(t)})/(-\sin\pi\alpha(t)), \quad (2.1)$$

where $\tau = \pm 1$ is the signature of the Regge pole with trajectory $\alpha(t)$. We envision EXD as being approximately valid before one applies the correction terms which in general break EXD.

Due to the assumption to maintain WSNZ one finds upon fitting the data that the resulting correction terms to single- and double-flip amplitudes are small. The correction terms to the non-flip amplitudes are, on the other hand, quite substantial and the resulting total amplitudes bear little resemblance to the input poles.

(b) Neglecting A_1 and $I=0$ Unnatural Parity Exchange

We make two assumptions that can easily be corrected if new data warrant.

Amplitudes with the t -channel quantum numbers of A_1 exchange and of $I=0$ unnatural parity exchange (e.g. π, h) are neglected. Existing data can be fit well using these assumptions; however, many of the predictions for double- and triple-spin observables do depend somewhat on them. In Sec III we discuss tests of possible A_1 exchange and $I=0$ unnatural parity exchange.

(c) Determination of Flip/non-flip Ratios from Meson-Baryon Scattering

Any analysis of NN scattering is complicated by the fact that there are five independent complex amplitudes $t_1, \dots, t_5$ and many possible Regge exchanges ($P, f, \omega, \rho, A_2, \pi, B$; see Table 1). The strengths of the couplings of these exchanges to the various t 's are, however, not completely arbitrary. Some knowledge concerning the natural parity exchanges can be gained by studying meson-baryon (MB) scattering. We have performed Regge-pole-plus-correction-term fits to $\pi N \rightarrow \pi N$ and $KN \rightarrow KN$ scattering and determined the $\bar{NN}$ helicity flip to non-flip ratios for the P, f, ω, ρ, A_2 exchanges given in Table 2. Notice, as is well known, the ρ and A_2 couple predominantly to helicity flip, whereas the P, f , and ω couple predominantly to helicity non-flip. Having determined these ratios we proceed to fit NN scattering assuming that

$$R = \text{flip/non-flip} = \left(\frac{H_{\omega}(s,t)}{\sqrt{-t} H_{\pi}(s,t)} \right)_{t=0}^{MB}$$

$$= \left(\frac{t_5(s,t)}{\sqrt{-t} t_1(s,t)} \right)_{t=0} = \left(\frac{t_2(s,t)}{t t_1(s,t)} \right)_{t=0}^{1/2} \quad (2.2)$$

The resulting solution is called "Normal-Regge" (see Table 4).

(d) Determination of the π and B Amplitudes from $\bar{pp}$ and np CHEX Scattering

The best determinations of π, B, ρ and A_2 exchange contributions to NN scattering come from a study of $\bar{pp}$ and np CHEX. Keeping the ρ and A_2 $\bar{NN}$ flip to non-flip ratios fixed at the values determined from meson-baryon scattering (Table 2) we determine the $I=1$ exchanges by fitting $d\sigma/dt$ and polarization data for $np \rightarrow pn$ and $\bar{pp} \rightarrow \bar{nn}$. The π, B, ρ , and A_2 poles and their respective correction terms π_c, B_c, ρ_c , and A_{2c} are then fixed and contributions to other NN processes from these exchanges are determined by isospin and G -parity. The resulting fits to $\bar{pp}$ and np CHEX are shown in Fig. 1 together with predictions for $d\sigma/dt(np \rightarrow pn)$ at FNAL energies. We include the following comments concerning fits to NN CHEX scattering:

- (i) The B exchange and its cut (B_c) contribution are crucial in understanding the sign and magnitude of the observed np CHEX polarization⁷⁾.
- (ii) In addition to the unnatural parity objects π and B the natural parity ρ and A_2 play a role in NN CHEX scattering. In particular since the ρ and A_2 exchanges do not decrease as fast with increasing energy as do the π_c and $B(B_c)$, the relative size of the pion cut spike at $t=0$ is predicted to change with increasing energy; the spike becoming less predominant (see Figs. 1c - 1d). This behavior has recently been verified by an np CHEX experiment at FNAL⁸⁾.

(e) Problems with "Normal-Regge" Model

Having determined the contributions to NN scattering from the π, B, ρ, A_2 and their associated cuts we proceed to fit data on pp, np , and $\bar{pp}$ elastic scattering keeping the P, f and ω $\bar{NN}$ helicity flip to non-flip ratios as determined from meson-baryon scattering (Table 2). The results of this fit called "Normal-Regge" are displayed in Fig. 2 and has the following properties:

- (i) The 6.0 GeV/c pp elastic data are well fit by "Normal-Regge."
 (ii) The solution does not extrapolate well to low energies. It fails to reproduce the rapid energy dependences seen in the pp polarization below $p_{lab} \approx 6.0$ GeV/c (Fig. 2b).
 (iii) The energy dependence of the " ω " exchange contribution is not sufficient to simultaneously reproduce the features of the difference $d\sigma/dt(\bar{p}p) - d\sigma/dt(pp)$ at 3.0 and 6.0 GeV/c (see Fig. 2a).
 (iv) The most embarrassing feature of "Normal-Regge" is that it predicts negative np elastic polarization at 6.0 GeV/c (see Fig. 2d), where recent data show clearly that the polarization is positive (at small t). In "Normal-Regge" the polarization arises primarily from the interference between the $I=0$ non-flip P, f and ω exchange amplitudes and the $I=1$ helicity flip ρ and A_2 exchange amplitudes, which changes sign in going from pp to np elastic scattering.

(f) "Regge- ω -flip" Model

Having failed to reproduce the features of NN scattering with a "Normal-Regge" approach we proceed to relax some of our assumptions and to allow more freedom (complexity) to the models. One obvious way to produce positive polarization in both pp and np elastic scattering is to allow for a larger " ω " flip coupling than that determined from meson-baryon processes. A substantial contribution to the polarization then arises from the $I=0$ helicity non-flip P and f interfering with the helicity flip $I=0$ ω , which does not change sign in going from pp to np scattering. The results of this approach are shown in Fig. 3 and have the following drawbacks:

- (i) The model fails to extrapolate to low p_{lab} . Again the rapid energy variation of the pp and np polarizations are not reproduced (Figs. 3b - 3d).
 (ii) Since a substantial contribution to the polarization comes from the helicity flip ω contribution, which changes sign in going from pp to $\bar{p}p$ elastic scattering, the model predicts the polarizations for these two processes to have opposite sign. Although the data on $\bar{p}p$ polarization are poor, both pp and $\bar{p}p$ appear to have the same sign polarizations (Fig. 3c).

(g) "Regge-Pom-flip" Model

Another way of producing positive polarizations for both pp and np elastic scattering is to allow for a substantial Pomeron helicity flip coupling. The results of such an approach are shown in Fig. 4. This model has the following properties:

- (i) Since the Pomeron contributes with the same sign to pp, pn, and $\bar{p}p$ elastic scattering, the resulting polarizations are all positive. (Figs. 4b - 4d).
 (ii) This model still suffers from the inability to extrapolate properly below $p_{lab} \approx 6.0$ GeV/c. In particular the rapid increase with decreasing energy seen in pp, np, and $\bar{p}p$ elastic polarization is not reproduced.
 (iii) The energy dependence of the " ω " contribution is still not adequate to reproduce the features of $d\sigma/dt(\bar{p}p) - d\sigma/dt(pp)$ at 3.0 and 6.0 GeV/c. (see Fig. 4a).

(h) "Super-Regge" Model

The previous three solutions are deficient in the following ways. The decrease with energy of the polarization is too slow, as is the decrease near $t=0$ of the difference $d\sigma/dt(\bar{p}p) - d\sigma/dt(pp)$ in all the solutions. The relative sign of the pp versus np polarization and the relative sign of $\bar{p}p$ versus pp polarization are difficulties with some approaches. Another difficulty which is not shown in the figures, is the failure of all of these models to reproduce the fall off with energy of the total pp and $\bar{p}p$ cross sections below 6 GeV/c. Finally (also not shown) none of these models do a good job in describing the behavior of Re/Im between 2 and 6 GeV/c. For both $\bar{p}p$ and pp, Re/Im changes sign from positive near 2 GeV/c becoming negative as the energy increases. For $\bar{p}p$ the energy dependence is very slight with Re/Im always small in magnitude while for pp Re/Im is as large as $\sim 30\%$ near 5 GeV/c. Reproducing the low energy sign change in Re/Im is impossible in the above approaches.

The key question at this point is: "Can all the above difficulties be 'explained' by a single missing ingredient?" The answer is yes! The missing ingredient can be parameterized as a pair of $l=0$ low-lying "effective" exchanges (which we call $\bar{w}$ and $\bar{f}$). The results of an approach which includes the $\bar{w}$ and $\bar{f}$ with intercepts near $\alpha(0) \approx -0.5$ are shown in Figs. 5-7. Note that when these exchanges are included the helicity flip to non-flip ratios of the "high lying" poles are very similar to the "Normal-Regge" solution (see Table 2).

The rapid energy dependence of the polarization and the fact that pp and $\bar{p}p$ polarizations have the same sign near $t=0$ can be understood if $\bar{f}$ contributes strongly to the helicity flip amplitude ϕ_3 while $\bar{w}$ approximately decouples. The energy dependence of $d\sigma/dt(\bar{p}p) - d\sigma/dt(pp)$ requires a strong contribution of $\bar{w}$ to the non-flip amplitude ϕ_1 . The energy dependence of Re/Im in $\bar{p}p$ and pp favors comparable contributions of $\bar{w}$ and $\bar{f}$ to ϕ_1 at $t=0$. The $\bar{w}$, $\bar{f}$ contributions to ϕ_2 and ϕ_4 are set to zero because there is as yet no way to isolate these amplitudes with sufficient accuracy to study such low-lying contributions to them. This approach has the ability of fitting all the existing pp, np, and $\bar{p}p$ elastic data from p_{lab} of about 3 to 20 GeV/c with the leading trajectories (P, f, w, ρ , A_2 , π , B) having parameter values completely consistent with what has been learned from other reactions. One is still left, however, with the problems of "theoretically" understanding why the lower lying objects $\bar{w}$ and $\bar{f}$ are so important in NN scattering but play little or no role in meson-baryon processes. We will speculate on this point in Sec. V.

(i) Kane Model

As mentioned in the introduction G. Kane has developed a model approach to two-body scattering processes based on Regge poles (R) plus absorptive corrections (P $\otimes$ R). In his approach the absorptive corrections are calculated from the Pomeron (P) and Regge poles (R) using a definite prescription and all

amplitudes are absorbed similarly. In order to reproduce the features of the data using this approach one must allow for great freedom of the input Regge poles (no WSNZ, non-EXD type signature factors) and in addition a sufficiently complicated Pomeron must be used. The complicated Pomeron is justified theoretically by the argument that it includes the effects of both elastic and inelastic intermediate states. Given these terms the absorptive corrections are calculated with no additional "fudge" factors. This approach is able to fit most of the experimental features of $PB \rightarrow PB^{(4)}$ and $PB \rightarrow VB^{(5)}$ processes and has recently been applied to NN scattering by C. Kane and A. Seidl⁽⁶⁾.

Both the "Kane-Model" and our "Super-Regge" solution describe well the available data near 6 GeV/c. However, due to the different assumptions about the nature of the input Regge poles and their absorptive corrections, these two approaches produce amplitudes for pp scattering which are in some ways quite different (Compare Fig. 7a-7b with Fig. 8a-8b). These differences in turn result in significantly different predictions for some of the as yet not measured observables (i.e. some of the HT-Lab observables (Table 3)). These differences and their significance will be discussed in detail in Sec. III.

III. New Observables and Predictions

(a) P, C_{NN} , D_{NN} , K_{NN}

Fits and predictions for P, C_{NN} , D_{NN} , and K_{NN} at 2, 3, 4, and 6 GeV/c for pp elastic scattering resulting from "Super-Regge" solution are shown in Figs. 5f-5g. The assumption of no " A_1 " type exchange amplitude results in $C_{NN} = K_{NN}$. In addition the neglect of any $l=0$ unnatural parity exchange contributions results in predicted D_{NN} values very close to one. The quantity D_{NN} is given symbolically by

$$D_{NN} = (|N|^2 - |U|^2) / (|N|^2 + |U|^2) \quad (3.1)$$

12.

where N and U correspond to natural and unnatural parity exchange amplitudes, respectively. If only $l=1$ unnatural parity exchanges are important then one can place a lower limit on D_{NN} by assuming that the experimental np CHEX differential cross section is pure unnatural parity. These limits are shown by dotted curves in Figs. 5f-5g. The model predicts D_{NN} values well within this limit due to sizable natural parity contributions to np CHEX scattering from ρ , A_2 , π_C and B_C . If forthcoming data on D_{NN} for pp elastic scattering lie below the limits shown in these figures, it will be necessary to include some unnatural parity $l=0$ exchange contributions to the models. In addition if K_{NN} does not equal C_{NN} " A_1 " type exchange contributions must be added.

(b) Halzen and Thomas CM Observables⁹⁾ (Table 3)

In Figs. 6a - 6d are displayed the predictions resulting from our "Super-Regge" fit for the Halzen and Thomas center-of-mass (HT-CM) observables $l(\text{Beam, Target, Scattered, Recoil})$ defined in Table 3. Notice that most of these observables are predicted to be near zero or ± 1 . This feature is common to many models and will be discussed in detail in Sec. IV.

(c) Halzen and Thomas Lab Observables⁹⁾ (Table 3)

The laboratory observables $l(\text{Beam, Target, Scattered, Recoil})$ for NN scattering defined in Table 3 are just those measured with a polarized beam scattering off a polarized target, with second scatterings performed to analyze the polarization of the scattered and recoil nucleon.

(i) pp Elastic Scattering

Some HT-Lab observables for pp elastic scattering resulting from our "Super-Regge" fit are shown in Figs. 6e - 6f. Notice that they are usually small or nearly equal to $\cos\theta_R$ or $\sin\theta_R$.

(ii) pp Elastic Scattering

Some HT-Lab observables for $\bar{p}p$ elastic scattering at 6.0 GeV/c resulting from our "Super-Regge" fit are shown in Figs. 6g - 6h. The $\bar{p}p$ elastic observables are quite different from those for pp elastic scattering. In particular they show considerable structure near $t = -0.6$ (GeV/c)² (see the A parameter in Fig. 6h). This structure is caused by the behavior of the dominant $N_0(s,t)$ amplitude. In pp elastic scattering P , f , and ω exchange contributions all add constructively to $N_0(s,t)$ (Figs 7g - 7i), whereas in $\bar{p}p$ the ω adds destructively to the $P + f$ contribution producing a dip in $N_0(s,t)$ plus a change in phase (Fig. 7c). This behavior results in the structures seen in the HT-Lab observables for $\bar{p}p$ scattering.

(iii) np Elastic Scattering

Some HT-Lab observables for np elastic scattering at 6.0 GeV/c resulting from our "Super-Regge" fit are shown in Figs. 6i - 6j. Many of the observables are predicted to be of opposite sign to those for pp elastic scattering. This is a consequence of the $l=1$ exchange contributions changing sign in going from pp to np elastic scattering.

(d) "Super-Regge" versus "Kane Model"

As discussed in Sec. 11 an attempt to consistently describe all the features of NN scattering from a model with a definite prescription for calculating the absorptive (Regge cut) correction terms has been presented by G. Kane and A. Seidl⁶⁾. Their model approach produces NN amplitudes which are in some ways similar to our "Super-Regge" solution but which also differ in many respects.

(1) Similarities

In both approaches $N_0(s,t)$ is the dominant amplitude at 6.0 GeV/c (Fig. 7a and Fig. 8a). This has the consequence that all the natural parity transversity amplitudes have nearly the same phase. We discuss this point further in Sec. IV.

(ii) Differences

Due to differences in the nature of the Regge poles and their respective absorptive corrections "Super-Regge" and "Kane Model" produce NN helicity amplitudes that differ greatly in their phase behavior (compare Figs. 7a - 7b and Figs. 8a - 8b). These phase differences result in different predictions for some of the HT observables (compare Figs. 9e - 9f and Figs. 6e - 6f). "Kane Model" and "Super-Regge" produce different predictions for the pp elastic scattering observables $I(s,0,0,s)$, $I(s,n,0,s)$, $I(s,s,0,0)$, $I(s,s,0,s)$, and $I(s,t,0,n)$. Let us examine these quantities a bit more closely.

1. $I(s,0,0,s)$ - This quantity is given by $I(s,0,0,s) = -\cos^2_R I(x,0,0,x) - \sin^2_R I(x,0,0,z)$. Both models produce very small values for $I(x,0,0,z)$ so the difference arises from $I(x,0,0,x) = 4 \operatorname{Re} N_0 U_2^*$ (assuming $U_0 = 0$; see Table 1). As can be seen by comparing N_0 and U_2 for "Super-Regge" (Figs. 7a - 7b) and "Kane Model" (Figs. 8a - 8b) the two approaches produce quite different phases for these amplitudes. The differences in U_2 can be traced back to the different way in which the two approaches produce the experimentally observed non-zero pp CHX polarization.

2. $I(s,n,0,s)$ - This quantity is given by $I(s,n,0,s) = -\cos^2_R I(x,y,0,x) + \sin^2_R I(x,y,0,z)$. Both models produce negligibly small values for $I(x,y,0,x)$ so the difference arises from $I(x,y,0,z) = 4 \operatorname{Im} N_0 U_2^*$ (assuming no A_1 exchange; see Table 1). Thus the different predictions from the two approaches for this observable are due to the same reason as (1.) above; the differences in the N_0 and U_2 amplitudes.

3. $I(s,s,0,0)$ - This quantity is given by $I(s,s,0,0) = 4 \operatorname{Re} N_0 U_2^*$ (assuming no A_1 exchange; see Table 1). It is amusing to note that since the models predict $I(x,0,0,z) \approx 0$ and have no A_1 exchange amplitudes they predict $I(s,0,0,s) = -\cos^2_R I(s,s,0,0)$.

4. $I(s,s,0,s)$ - This quantity is given by $I(s,s,0,s) = -\cos^2_R I(y,x,0,x) - \sin^2_R I(y,x,0,z)$, where from Table 1 $I(y,x,0,x) = -4 \operatorname{Im}(N_0 + N_2) N_1^*$ and in the absence of A_1 exchange $I(y,x,0,z) = -4 \operatorname{Im} N_0 N_2^*$. Both approaches give similar results for $I(y,x,0,x)$ because with N_2 small $\operatorname{Im} N_0 N_1^*$ is related to the polarization and both models fit the polarization. The approaches differ in their predictions for $\operatorname{Im} N_0 N_2^*$ due to the differing phases of N_0 and N_2 (see Figs. 7a - 7b and Figs. 8a - 8b). A good determination of this quantity would be extremely useful in constraining the model approaches.

5. $I(s,t,0,n)$ - This quantity is equal to $I(x,z,0,y) = -4 \operatorname{Im} N_0 U_2^*$ (assuming no A_1 exchange - Table 1), which differs in the two approaches as we have seen in (1), (2), and (3) above. In fact assuming no A_1 exchange and neglecting $I(x,y,0,x)$ yields $I(s,n,0,s) = -\sin^2_R I(s,t,0,n)$.

(iii) Significance of Differences

The question now arises as to the significance of the differences between "Super-Regge" and "Kane Model" in the above pp elastic observables. If one measures $I(s,0,0,s)$, for example, and it disagrees with "Kane Model" does this rule out the model or can one just readjust the parameters slightly to agree with the new results? The answer to this question is complicated and will probably depend on whom you ask. Here are some points that must be considered, however:

1. Both "Super-Regge" and "Kane Model" neglect " A_1 " type exchange amplitudes and neglect any possible $I=0$ unnatural parity exchange contributions (i.e. ρ, η). This is reasonable since at present there is no evidence that these objects are necessary in NN scattering. However, if forthcoming experiments indicate the presence of such terms they can be easily incorporated into anyone's model.

2. "Kane Model" does not extrapolate well below 6.0 GeV/c. The model does not include the effects we parameterize by lower lying $I=0$ and I objects necessary to fit data below 6.0 GeV/c and which are included in "Super-Regge". These objects could easily be incorporated into "Kane Model" allowing it to extrapolate properly below 6.0 GeV/c, but would also change slightly the results at 6.0 GeV/c and above.

In spite of these reservations the determination of $N_0 U_2^*$ by measurements of $I(x,0,0,x)$ (see (1) above) and $I(x,y,0,z)$ (see (2) above) should be fairly clean. In the first case we are neglecting $\text{Re } N_2 U_0^*$ relative to $\text{Re } N_0 U_2^*$ and in the second case neglecting $\text{Im } N_2 U_0^*$ relative to $\text{Im } N_0 U_2^*$, and since most likely N_2 is much smaller than the dominant N_0 amplitude this approximation should be good even if U_0 is not precisely zero. Now if the relative phase between N_0 and U_2 turns out to be significantly different than that predicted by Kane's Model his assumptions concerning the nature of the input Regge poles and prescription of calculating absorptive effects will be in serious trouble. If, on the other hand, this phase turns out to be significantly different than that predicted by our "Super-Regge" fit we will be forced to drastically change our thinking concerning the nature of the Regge poles and their correction terms.

IV. Transversity Amplitudes

(a) Definition

It is convenient when discussing nucleon-nucleon scattering to define five complex transversity amplitudes as shown in Table 1. The quantities $T_{\lambda_c \lambda_d \lambda_a \lambda_b}(s,t)$ refer to amplitudes with spin quantized along the normal to the production plane ($\hat{n} = (\vec{p}_a \times \vec{p}_c)/|\vec{p}_a \times \vec{p}_c|$). These amplitudes have the nice property that the observable quantities $d\sigma/dt$, P , C_{NN} and D_{NN} are related to their magnitudes as follows:

$$\frac{d\sigma}{dt} = |T_{++++}|^2 + |T_{----}|^2 + 2|T_{+--+}|^2 + 2|T_{-+-}|^2 + 2|T_{+-}|^2 \quad (4.1a)$$

$$P \frac{d\sigma}{dt} = |T_{++++}|^2 - |T_{----}|^2 \quad (4.1b)$$

$$C_{NN} \frac{d\sigma}{dt} = |T_{++++}|^2 + |T_{----}|^2 - 2|T_{+--+}|^2 + 2|T_{-+-}|^2 - 2|T_{+-}|^2 \quad (4.1c)$$

$$D_{NN} \frac{d\sigma}{dt} = |T_{++++}|^2 + |T_{----}|^2 + 2|T_{+--+}|^2 - 2|T_{-+-}|^2 - 2|T_{+-}|^2 \quad (4.1d)$$

(b) Experimentally Determined Quantities

Given experimental measurements of $d\sigma/dt$, P , and C_{NN} one can determine the following three transversity cross sections:

$$\frac{d\sigma_{++}}{dt} = |T_{++++}|^2 + |T_{+--+}|^2, \quad (4.2a)$$

$$\frac{d\sigma_{+-}}{dt} = |T_{----}|^2 + |T_{-+-}|^2, \quad (4.2b)$$

$$\frac{d\sigma_{\uparrow\uparrow}}{dt} = |T_{+--+}|^2 + |T_{-+-}|^2, \quad (4.2c)$$

where

$$\frac{d\sigma}{dt} = \frac{d\sigma_{++}}{dt} + \frac{d\sigma_{+-}}{dt} + 2 \frac{d\sigma_{\uparrow\uparrow}}{dt}. \quad (4.2d)$$

The experimental data on these transversity cross sections for pp elastic scattering at 6.0 GeV/c are shown in Fig. 10 together with the predicted curves from "Normal-Regge," "Regge- ω -flip," "Regge-Pom-flip," and "Super-Regge" fits. All these models fit the above cross sections because they all fit $d\sigma/dt$, P , and C_{NN} for pp elastic scattering at 6.0 GeV/c.

Defining $T_{++++}(s,t)$ to be purely imaginary we see (from (4.1)) that our existing experimental knowledge about the four transversity amplitudes (neglecting A_1 exchange implies $T_{+--+} = T_{-++-}$; see Table 1) can be summarized as follows:

- (i) We know the natural parity transversity magnitudes $|T_{++++}|$, $|T_{+--+}|$, and $|T_{-++-}|$ within some error.
- (ii) We have an upper limit on the unnatural parity transversity magnitude $|T_{+--+}|$.
- (iii) We know nothing about the relative phases between the transversity amplitudes.

This means that on an Argand diagram T_{+--+} and T_{-++-} lie somewhere within a ring about the origin and T_{++++} lies somewhere within a circle (see Fig. 11).

Our experimental knowledge of the s-channel helicity amplitudes $N_0(s,t)$, $N_1(s,t)$, $N_2(s,t)$, and $U_2(s,t)$ (see Table 1) is more complicated to exhibit due to the connections between the transversity and helicity frame. Fig. 12a shows a randomly generated plot of the possible regions for these helicity amplitudes (defining N_0 to be imaginary).

(c) Model Predictions

Fig. 11 also shows vectors corresponding to the predictions of the transversity amplitudes resulting from "Super-Regge." Although the relative phases between T_{++++} , T_{+--+} , and T_{-++-} could be anything and fit existing data the models result in these phases being small. This is better illustrated in Fig. 12 where we display the phases and relative phases of the transversity amplitudes resulting from various model approaches including "Kane Model". In every case the relative phases between the large natural parity amplitudes T_{++++} , T_{+--+} , and T_{-++-} are small. This is due to the dominance of the $N_0(s,t)$ amplitude in these models. Fig. 12a shows that existing data cannot determine well the magnitude $|N_0(s,t)|$, however all models have this magnitude almost maximal. In elastic scattering the Pomeron + t helicity non-flip amplitude dominates. This will clearly be

the case near $t=0$ from total cross section information; however, in the model fits this remains the case out to fairly large t (see Figs. 7a-b, 8a-b). All the various model approaches including "Kane Model" have this property. The natural parity transversity phases seldom differ by more than $10^\circ - 12^\circ$. The models do differ in the signs of these small phase differences and it is these differences that characterize the various model approaches. All models predict about the same transversity magnitudes and have small phases between T_{++++} , T_{+--+} , and T_{-++-} . In addition all models produce very small magnitudes for the unnatural parity amplitudes $|T_{+--+}| = |T_{-++-}|$, but the phase between this amplitude and the three natural parity amplitudes need not be small.

We can now understand why the models predict that the majority of the HT-CN observables are near zero or ± 1 . These CN observables measure one of the following (see Table 3):

(i) Combinations of sums and/or differences of the squared magnitudes of the transversity amplitudes.

(ii) Sines or cosines of the relative phases between the three natural parity transversity amplitudes T_{++++} , T_{+--+} , T_{-++-} .

(iii) Sines or cosines of the relative phases between the unnatural parity transversity amplitudes T_{+--+} (or T_{-++-}) and one of the natural parity amplitudes T_{++++} , T_{+--+} , T_{-++-} , times the magnitude $|T_{+--+}|$ (or $|T_{-++-}|$). Observables of type (i) are essentially known from existing data since we already have a fairly good determination of the transversity magnitudes. Observables of type (ii) are near zero for $\sin_{rel}$ and near ± 1 for $\cos_{rel}$, since $\phi_{rel} \approx 0$. In this case it is clearly advantageous to measure observables proportional to $\sin_{rel}$ rather than $\cos_{rel}$. Observables of type (iii) are small because $|T_{+--+}|$ is small even though in this case $\sin_{rel}$ may not be small. Consider the following examples from Table 3:

1. $I(0, z, 0, z)$ - This quantity is given by $I(0, z, 0, z) = 2\text{Re}(T_2 T_3^* - T_1 T_3 - 2T_4 T_5^*) / (|T_1|^2 + |T_2|^2 + |T_3|^2 + 2|T_4|^2 + 2|T_5|^2) = 1$; since $\text{Re} T_2 T_3^* = |T_2| |T_3|$, and $\text{Re} T_1 T_3 = |T_1| |T_3|$ and $|T_1| = |T_2| = |T_3|$ and $|T_4| = |T_5| = 0$. The models predict about one for the quantity as can be seen in Fig. 6a and Fig. 9a.

2. $I(0, z, 0, x)$ - This quantity is given by $1/2 \ln(T_1 T_3^* - T_2 T_3) \approx 0$ since $\text{Im} T_1 T_3^* = \sin \delta_R \approx 0$ and similarly for $\text{Im} T_2 T_3$. Comparing $I(0, z, 0, x)$ for "Super-Regge" (Fig. 6a) and "Kane Model" (Fig. 9a) shows that indeed this observable is predicted to be small, but that there are important differences in the sign which characterize the two approaches. Whether quantities like $I(0, z, 0, x)$ can be measured with enough accuracy to distinguish the two approaches is, of course, another question.

V. Summary and Conclusions

We make the following comments concerning our analysis of the NN scattering system:

1. A "Normal-Regge" model containing the usual exchanges (P, f, ω , A_2 , π , B) plus correction terms, with the pole NN helicity flip to non-flip ratios fixed from meson-baryon scattering data, is not capable of reproducing the features of existing NN $\rightarrow$ NN data. In particular this approach predicts negative np elastic polarization at 6.0 GeV/c in disagreement with recent data (see Fig. 2d).

2. The energy dependences of the elastic pp and np polarizations, and the energy dependence of the line reversal difference $d\sigma/dt(\bar{p}p) - d\sigma/dt(pp)$, and the energy dependence of the total cross section and Re/Im in the region 2.0 - 6.0 GeV/c indicate the presence of additional effects not accounted for by "Normal-Regge." We parameterize these effects by including a lower lying $\bar{f}$ and $\bar{\omega}$ pole ($\alpha(0) \approx -0.5$) coupling to ϕ_1 , ϕ_3 , and ϕ_5 ("Super-Regge"). We stress, however, that this is merely a parameterization of effects seen in the data. The physics behind the parameterization may be

that of s-channel effects¹⁰⁾ (opening up of inelastic thresholds) or perhaps Regge-Regge cuts. Another interesting possibility is that the $\bar{f}$ and $\bar{\omega}$ are related to the exotic exchanges predicted by baryon-baryon scattering duality diagrams, (i.e. $2q\bar{q}$ exotic states) which are not expected in meson-baryon processes^{11,12}.

3. "Super-Regge" is capable of fitting all the existing data on NN scattering down to 3.0 GeV/c and some observables down to 2.0 GeV/c! There is an extremely rapid energy variation of the t_2 amplitude below 3.0 GeV/c resulting in the observed rapid rise with decreasing energy of $\sigma_{\pi\pi} - \pi_{\pi\pi}$ (Fig. 5b) seen in the data that is not accommodated even by "Super-Regge." This is a most interesting effect that is probably due to the opening up of specific inelastic channels of the pp system¹⁰⁾ which reflect on the elastic amplitude via unitarity and the optical theorem.

4. It is very difficult to distinguish among various Regge exchange models (like "Kane" and "Super-Regge") by measurements of pp elastic scattering at 6.0 GeV/c. First a systematic study must be made to ascertain the importance of the A_1 exchange force and I=0 unnatural parity exchanges (neglected by all models). In addition a careful examination of energy dependences between 2.0 and 4.0 GeV/c must be performed to determine the precise nature and importance of the $\bar{f}$ -effects we parameterized by $\bar{f}$ and $\bar{\omega}$. (Fig. 5 shows that the $\bar{f}$ and $\bar{\omega}$ produce a non negligible effect even at 6.0 GeV/c). Then careful measurements of observables like $I(s, 0, 0, s)$ or $I(n, s, 0, s)$ should distinguish among the various absorption prescriptions.

5. Double- and triple-spin measurements performed on np CHX scattering (polarized deuterium target!) are much more useful in distinguishing among Regge pole plus absorption models. This process does not involve the little understood Pomeron and in a purely EXD world would have zero polarization (i.e. $\rho - A_2 = \text{real}$, $\pi - B = \text{real}$). The main difference in existing models lies

in the mechanism by which they fit the non-zero np CHEX polarization. Kane's approach is to completely abandon EXD for the input Regge poles in which case producing a non-zero polarization is no problem. In our approach the ρ , A_2 and π , B input poles are roughly EXD (the ρ , A_2 more so than the π , B) and it is the absorption corrections that break EXD thereby allowing for non-zero polarization. We must know how in nature this polarization arises and detailed spin measurements should tell us.

6. Because t-channel quantum numbers are important it is crucial to make measurements in elastic channels other than just pp (e.g. np, $\bar{p}p$). The models predict quite different behavior for many observables in np and $\bar{p}p$ compared with pp. For example, the 6.0 GeV/c $\bar{p}p$ observables show remarkable structure due to the sign change of the ω exchange contribution. In np elastic scattering the C_{NN} parameter is predicted to be negative at 6.0 GeV/c rather than positive as in pp scattering.

7. In our opinion the importance of experiments on the NN system in the region 7.0 - 12.0 GeV/c should not be judged solely by their ability to verify or rule out a particular Regge model (like "Kane" or "Super-Regge"). This is very difficult and the models probably don't warrant such attention. Instead one should view spin- and double-spin measurements on the NN system in a more general framework. From existing data we do not even know if it is the helicity non-flip amplitude N_0 or the double-flip amplitude N_2 that dominates the scattering process at 6.0 GeV/c (see Fig. 11d). All Regge models say that N_0 dominates but this has not been verified experimentally yet. In addition NN scattering between 1.0 and 3.0 GeV/c is characterized by rapid energy dependent effects presumably due to inelastic channels opening up and careful measurements of pp, np and $\bar{p}p$ will teach us about unitarity and duality. Comparisons of pp, np, and $\bar{p}p$ elastic scattering

at 6.0 GeV/c demonstrate the importance of t-channel quantum numbers. The fact that the pp and np elastic polarizations are different at 6.0 GeV/c already rule out a whole class of purely geometric models.¹³⁾

8. In this analysis we have limited ourselves to small t ($|t| \leq 1.5(\text{GeV}/c)^2$); however measurements at larger t can be quite interesting. If the Pomeron is a geometric like object with several diffractive minima then such structure could not be detected in $d\sigma/dt$ at 6.0 GeV/c due to the overwhelming presence of the t-channel exchange forces due to ρ , A_2 , f, π , etc. On the other hand, since the polarization is given roughly by the Pomeron interfering with the Regge exchange contributions, one might expect to see considerable structure in the polarization at large t. This seems to be the case experimentally. Similar structure in np elastic polarization is expected and data on this would be most interesting.

Acknowledgements

We would like to acknowledge useful discussions with G. C. Fox, G. L. Kane, and G. Thomas and A. B. Wicklund.

References

1. See, for example; V. Barger, "Reaction Mechanisms at High Energy," and R. D. Field, "Some Aspects of Two Body Phenomenology," in *Proceedings of the XVII International Conference on High Energy Physics*, London, 1974.
2. See, for example, G. C. Fox, "On the Importance of Being an Amplitude," in *Phenomenology in Particle Physics*, 1971 and R. D. Field, "Amplitude Analyses of Hypercharge Exchange Reactions," in *AIP Conference Proceedings No. 13 Particles and Fields* subseries No. 5, Ed. by P. K. Williams and V. Hagopian.
3. See, for example, R. Diebold, Rapporteur's Talk at the Aix en Provence Conference (1973) and Ref. 5.
4. B. J. Hartley and G. L. Kane, *Nucl. Phys.* B57, 157 (1973).
5. R. D. Field and Deepinder P. Sidhu, *Phys. Rev.* D10, 89 (1974).
6. G. L. Kane and A. Seidl, "An Interpretation of Two-Body Hadron Reactions," UMHE75-18 (to be published).
7. This result was obtained previously by J. F. Owens, "np and $\bar{p}p$ Charge Exchange Polarization and Effective Absorption Models," Case Western Reserve University, preprint (1974) unpublished.
8. Data presented by N. Reay at the 1975 Seattle meeting, APS.
9. F. Halzen and G. H. Thomas, *Phys. Rev.* D10, 344 (1974).
10. G. L. Kane and G. H. Thomas, "Importance of the NA Inelastic Threshold for Understanding Low Energy NN Amplitudes," ANL-HEP-PR-75-56.
11. J. L. Rosner, *Phys. Rev. Letters* 21, 950 (1968); *Phys. Rev. Letters* 22, 689 (1969).
12. See also, Jan W. Dash and Henri Navelet, "Evidence for a Low-lying unrenormalized Vacuum Trajectory from NN Scattering," IBL-4215 (to be published).
13. See, for example, Francis Halzen, "Theoretical Interpretation of Experiments with Polarized Proton Beams," in *Proceedings of the Summer Study on High-Energy Physics with Polarized Beams*, Argonne, 1974, (ANL-HEP 75-02).

Table 1. Definition of Various Scattering Amplitudes for

$$N_a N_b \rightarrow N_c N_d$$

(a) Definition of $\phi_i(s, t)$ in terms of s-channel helicity amplitudes

$$H_{\lambda_c \lambda_d; \lambda_a \lambda_b}(s, t).$$

$$\phi_1 = H_{++++} = H_{----}$$

$$\phi_2 = H_{+-+} = H_{-+-}$$

$$\phi_3 = H_{+--} = H_{-++}$$

$$\phi_4 = H_{-+-} = H_{+--}$$

$$\phi_5 = H_{+++} = -H_{---}$$

$$\phi_5 = -H_{+-+} = H_{-+-}$$

$$\phi_5 = -H_{+--} = H_{-++}$$

$$\phi_5 = -H_{-+-} = H_{+--}$$

(b) Definition of $N_i(s, t)$ and $U_i(s, t)$ amplitudes in terms of $\phi_i(s, t)$. These amplitudes project out natural and unnatural parity in the t-channel (in the limit s large), respectively.

$$N_0 = 1/2(\phi_1 + \phi_3)$$

$$N_1 = \phi_5$$

$$N_2 = 1/2(\phi_4 - \phi_2)$$

$$U_0 = 1/2(\phi_1 - \phi_3)$$

$$U_2 = 1/2(\phi_4 + \phi_2)$$

Table 1. (continued)

(c) Definition of the transversity amplitudes $T_{\lambda_c \lambda_d; \lambda_a \lambda_b}(s, t)$ in terms of $N_i(s, t)$ and $U_i(s, t)$ and (for completeness) in terms of the ϕ_i 's.

$$T_1 = T_{++++} = (N_0 - N_2 - 2iN_1)/\sqrt{2} = (\phi_1 + \phi_2 + \phi_3 - \phi_4 - 4i\phi_5)/(2\sqrt{2})$$

$$T_2 = T_{----} = (N_0 - N_2 + 2iN_1)/\sqrt{2} = (\phi_1 + \phi_2 + \phi_3 - \phi_4 + 4i\phi_5)/(2\sqrt{2})$$

$$T_3 = T_{+-+} = (N_0 + N_2)/\sqrt{2} = (\phi_1 - \phi_2 + \phi_3 + \phi_4)/(2\sqrt{2})$$

$$T_4 = T_{+--} = (-N_0 - N_2)/\sqrt{2} = (-\phi_1 - \phi_2 + \phi_3 - \phi_4)/(2\sqrt{2})$$

$$T_5 = T_{-+-} = (N_0 - N_2)/\sqrt{2} = (\phi_1 - \phi_2 - \phi_3 - \phi_4)/(2\sqrt{2})$$

(d) t-channel exchanges contributing to the various $N_i(s, t)$ and $U_i(s, t)$ amplitudes for NN scattering.

Amplitude	NN $\rightarrow$ NN	NN CHEx
N_0	P, f, ω, ρ, A_2 $f_c, \omega_c, \rho_c, A_2^c$	ρ, A_2, ρ_c, A_2^c
N_1	P, f, ω, ρ, A_2 $f_c, \omega_c, \rho_c, A_2^c$	ρ, A_2, ρ_c, A_2^c
N_2	P, f, ω, ρ, A_2 $f_c, \omega_c, \rho_c, A_2^c$ π_c, B_c	ρ, A_2, ρ_c, A_2^c π_c, B_c
U_0	A_1	A_1
U_2	π, B, π_c, B_c $f_c, \omega_c, \rho_c, A_2^c$	π, B, π_c, B_c ρ_c, A_2^c

Table 1. (continued)

(e) Normalization - we have normalized so that

$$\begin{aligned} \frac{d\sigma}{dt} &= |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2 \\ &= 2(|N_0|^2 + 2|N_1|^2 + |N_2|^2 + |U_0|^2 + |U_2|^2) \\ &= |T_1|^2 + |T_2|^2 + 2|T_3|^2 + 2|T_4|^2 + 2|T_5|^2 \end{aligned}$$

Table 2. Helicity flip to non-flip ratio R for various model approaches to NN scattering, where for a given Regge pole in meson-baryon scattering we define $R = H_{+-}(s,t)/(\sqrt{-t} H_{++}(s,t))$ evaluated at $t=0$. Similarly for NN scattering $R = \phi_5(s,t)/(\sqrt{-t} \phi_1(s,t)) = (\phi_2(s,t)/(\sqrt{-t} \phi_1(s,t)))^{1/2}$ evaluated at $t=0$. For individual Regge poles these ratios are independent of s .

	P	f	w	p	$\frac{A_2}{A_1}$
Meson-Baryon fits	0	0.04	0.15	4.2	4.6
Normal-Regge	0	0.04	0.15	4.5	4.5
Regge-w-flip	0	0.05	0.52	4.5	4.5
Regge-Pom flip	-0.29	0.13	0.18	4.5	4.5
Kane-Model ⁶⁾	0	0.13	0.09	7.07	3.27
Super-Regge	0	0.0	0.15	4.5	4.5

Table 3. (continued)

[illegible]

Table 3. The Halzen and Thomas (Ref. 4) Lab and CM observables in terms of the s-channel helicity amplitudes and in terms of the transversity amplitudes defined in Table 1. The laboratory observables L(Beam, Target, Scattered, Recoil) for $NN \rightarrow NN$ are defined with respect to a frame for each particle such that $\hat{n}$ is along the normal to the scattering plane, $\hat{k}$ is along the direction of motion and $\hat{s} = \hat{n} \times \hat{k}$ is in the scattering plane. Since the target is at rest and $\hat{k}$ is undefined, by convention one uses for the target the beam unit vectors. The angles ϑ_L and ϑ_R are the laboratory scattering and recoil angles, respectively. These observables are just those measured with a polarized beam scattering off a polarized target, with second scatterings performed to analyze the polarizations of the scattered and recoil nucleon. In general, given the cross section $\sigma(2,2,2,2)$ where each initial particle is polarized and each final particle's polarization analyzed parallel (+) or antiparallel (-) to a given direction $\hat{n}$, $\hat{k}$, or $\hat{s}$, the ratio of the corresponding HT observable in the table to the unpolarized cross section is the ratio $\sum n_i n_a n_b n_c n_d = \sigma(n_a, n_b, n_c, n_d) / \sum \sigma(n_a, n_b, n_c, n_d)$, where $n_i = \pm 1$. If an initial particle is unpolarized or a final particle's polarization is not analyzed, delete the corresponding factor n_i and omit that particular summation. The vectors x, y, and z denote the center of mass helicity frame directions. Their relationship to $\hat{n}$, $\hat{k}$ and $\hat{s}$ for each particle can be inferred from the table.

(Table 3 continued on next page.)

(Table 3 continued on next page.)

Table 3. Description of various model approaches to NN scattering,

where the subscript c refers to corrections terms (Regge-cuts, Regge-Regge cuts) applied to the corresponding Regge pole.

Name	Exchanges	Description
Normal-Regge	$P, f, \omega, \rho, A_2, \pi, B,$	Helicity flip/non-flip ratios
	$f_c, \omega_c, \rho_c, A_2^c, \pi_c, B_c$	determined from meson-baryon scattering.
Regge- ω -flip	$P, f, \omega, \rho, A_2, \pi, B,$	Similar to Normal Regge but with
	$f_c, \omega_c, \rho_c, A_2^c, \pi_c, B_c$	large ω helicity flip contribution.
Regge-Pom-flip	$P, f, \omega, \rho, A_2, \pi, B,$	Similar to Normal Regge but with
	$f_c, \omega_c, \rho_c, A_2^c, \pi_c, B_c$	sizable Pomeron helicity flip coupling.
Kane-Model	$P, f, \omega, \rho, A_2, \pi, B,$	A model for high-energy two-body
	$f_c, \omega_c, \rho_c, A_2^c, \pi_c, B_c$	scattering presented by Kane and Seidl (Ref. 6). Poles do not have WSNZ and all amplitudes (helicity flip and non-flip) are absorbed strongly.
Super-Regge	$P, f, \omega, \rho, A_2, \pi, B,$	Similar to Normal-Regge but including
	$f_c, \omega_c, \rho_c, A_2^c, \pi_c, B_c$ and f, ω .	lower lying ($\alpha(0) \approx -0.5$) $l=0$ vector (ω) and tensor (f) contributions. This approach is capable of reproducing the features of the data from $p_{lab} = 3.0$ GeV/c and up.

Table 5. Successes and Failures of the various model approaches to NN scattering described in Table 4, where low (high) refer to $p_{lab} < 6.0$ GeV/c ($p_{lab} \geq 6.0$ GeV/c).

	<u>pp $\rightarrow$ pp</u>		<u>$\bar{p}p \rightarrow \bar{p}p$</u>		<u>pn $\rightarrow$ pn</u>		<u>Figure</u>
	Low	High	Low	High	Low	High	
Normal-Regge	Bad	Good	Bad	OK	Bad	Bad	2
Regge- ω -flip	Bad	Good	Bad	Bad	Bad	OK	3
Regge-Pom-flip	Bad	Good	Bad	Good	Bad	OK	4
Kane-Model	Bad	Good	Bad	Good	Bad	Good	Ref. 6
Super-Regge	Good	Good	Good	Good	Good	Good	5

- Fig. 1 (a) Fit to np CHEX differential cross section data at 3.0, 11.0, and 25.0 GeV/c. The fit contains the π , B, ω , A_2 Regge poles plus their associated correction terms (Regge cuts: π_c , B_c , ω_c , and A_2^c).
- (b) Same as (a) but with an expanded t scale and with predictions at 50, 100, and 200 GeV/c.
- (c)-(d) Predictions for np + pn at 75, 105, 140, 180, 222, and 260 GeV/c. Notice the decrease in the height of the π -cut spike relative to the ω - A_2 background. These predictions agree perfectly with recent FNAL data (Ref. 8).
- (e) Fit to np CHEX polarization data from an amplitude parameterization containing a π , B, ρ and A_2 Regge poles plus their associated correction terms, (π_c , B_c , ρ_c , and A_2^c). In our approach the contributions from the B_c are crucial in reproducing the observed size and energy dependence of this polarization.
- (f) Same as (a) but for $\bar{p}p$ CHEX.
- Fig. 2 (a) Fit to pp and $\bar{p}p$ elastic scattering at 3.0 and 6.0 GeV/c from an amplitude parameterization that contains |1| contributions (determined from Fig. 1) and the P, f and ω Regge poles plus their correction terms (f_c and ω_c). This fit ("Normal-Regge") maintains the f and ω helicity flip/non-flip ratios (see Table 2).
- (b) Comparison of the results for "Normal-Regge" with pp elastic polarization data. The agreement is satisfactory for $p_{lab} \geq 6.0$ GeV/c, but this approach fails to extrapolate down even to 4.0 GeV/c.
- (c) Comparison of the results for "Normal-Regge" with $\bar{p}p$ elastic polarization data.
- (d) Comparison of the results for "Normal-Regge" with np elastic polarization data. This approach predicts negative polarization in contradiction to the data!

- Fig. 3 (a) Fit to pp and $\bar{p}p$ elastic scattering at 3.0 and 6.0 GeV/c from an amplitude parameterization that contains |1| contributions (determined from Fig. 1) and the P, f and ω Regge poles plus their correction terms (f_c and ω_c) and where ω is allowed to have a considerable helicity flip coupling ("Regge- ω -flip"; see Table 2).
- (b) Comparison of the results for "Regge- ω -flip" with pp elastic polarization data. The agreement is satisfactory for $p_{lab} \geq 6.0$ GeV/c, but this approach fails to extrapolate down below 6.0 GeV/c.
- (c) Comparison of the results for "Regge- ω -flip" with $\bar{p}p$ elastic polarization data. This approach predicts negative polarization at small $-\ln t$ in disagreement with data.
- (d) Comparison of the results for "Regge- ω -flip" with np elastic polarization data. The agreement is satisfactory, at 6.0 GeV/c, but this approach fails to extrapolate down even to $p_{lab} = 4.0$ GeV/c.
- Fig. 4 (a) Fit to pp and $\bar{p}p$ elastic scattering at 3.0 and 6.0 GeV/c from an amplitude parameterization that contains |1| contributions (determined from Fig. 1) and the P, f and ω Regge poles plus their correction terms (f_c and ω_c) and where the Pomeron P is allowed to develop a sizeable helicity flip coupling ("Regge-Pom-flip"; see Table 2).
- (b) Comparison of the results for "Regge-Pom-flip" with pp elastic polarization data. The agreement is satisfactory for $p_{lab} \geq 6.0$ GeV/c, but this approach fails below 6.0 GeV/c.
- (c) Comparison of the results for "Regge-Pom-flip" with $\bar{p}p$ elastic polarization data.

- (d) Comparison of the results for "Regge-Pom-flip" with np elastic polarization data. The agreement is satisfactory at 6.0 GeV/c, but this approach fails to extrapolate down even to 4.0 GeV/c.

Fig. 5 (a) Fit to pp and $\bar{p}p$ elastic scattering at 3.0 and 6.0 GeV/c

- from an amplitude parameterization that contains $l=1$ contributions (determined from Fig. 1) and the P, f, and ω Regge poles plus their associated correction terms ($\tilde{f}_c$ and $\tilde{\omega}_c$). In addition "Super-Regge" contains lower lying ($\tilde{f}$ and $\tilde{\omega}$) $l=0$ contributions whose intercepts are about -0.5 (see Table 2).
- (b) Shows the pp and $\bar{p}p$ total cross sections; Real to Imaginary ratios at $t=0$ ($\bar{p}p$ = dashed, pp = solid); and the transversity spin total cross section difference $\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}$ for pp scattering resulting from "Super-Regge." This approach does not produce the rapid rise in this observable below $p_{lab} = 3.0$ GeV/c even with the presence of $\tilde{f}$ and $\tilde{\omega}$. This rise is caused by an additional effect (probably an s-channel effect due to inelastic thresholds) in addition to "Super-Regge" (see Ref. 10).
- (c) Comparison of the results for "Super-Regge" (solid curve) with pp elastic polarization data. The agreement is excellent down to 2.0 GeV/c! To illustrate the role played by the $\tilde{f}$ and $\tilde{\omega}$ we display the results from "Super-Regge" with these contributions set to zero (dashed curve).
- (d) Same as (c) but for $\bar{p}p$ elastic polarization.
- (e) Same as (c) but for np elastic polarization.
- (f)-(g) Predictions for the polarization, C_{NN} , D_{NN} and K_{NN} for pp elastic scattering at 2.0, 3.0, 4.0, and 6.0 GeV/c resulting from "Super-Regge" (solid curves). Because of the assumption of no " A_1 -like" exchange contributions $C_{NN} = K_{NN}$. (This is a good experimental

way to test this assumption.) The dotted curves represent lower bounds on D_{NN} based on the assumption that all unnatural parity exchange contributions are $l=1$ and that the experimental np CHEX ds/dt is purely unnatural parity exchange (clearly an over-estimate). If forthcoming data lie below the dotted curves it will be necessary to include $l=0$ unnatural particle exchange contributions to the models for NN scattering.

- (h)-(i) Same as (f)-(g) but for $\bar{p}p$ elastic scattering.
 (j)-(k) Same as (f)-(g) but for np elastic scattering.

Fig. 6

- (a)-(d) Predictions for the MT-CM (center of mass) observables defined in Table 3 for pp elastic scattering at 6.0 GeV/c resulting from "Super-Regge."
- (e)-(f) Predictions for some of the MT-LAB observables defined in Table 3 for pp elastic scattering at 6.0 GeV/c resulting from "Super-Regge." These observables are either being measured now or will be measured in the near future. The dotted curves correspond to either $-\cos\theta_R$ or $\sin\theta_R$.
- (g)-(h) Same as (e)-(f) but for $\bar{p}p$ elastic scattering at 6.0 GeV/c.
- (i)-(j) Same as (e)-(f) but for np elastic scattering at 6.0 GeV/c.

Fig. 7

- (a)-(b) Amplitudes for pp elastic scattering resulting from "Super-Regge" at 6.0 GeV/c. The amplitudes are in units of $[mb/(\text{GeV}/c)^2]^{1/2}$ and have been multiplied by $e^{-2.5t}$. The amplitude U_0 is assumed to be zero (no " A_1 -like" exchange, see Table 1).
- (c)-(d) Same as (a)-(b) but for $\bar{p}p$ elastic scattering.
- (e)-(f) Same as (a)-(b) but for np elastic scattering.

- (g) Vectors corresponding to the contribution to the N_0 amplitude at $p_{lab} = 6.0$ GeV/c and $t=0.0$ (GeV/c)² from the Pomeron (dot-dash), f (dashed), and ω (dotted) exchanges for pp, $\bar{p}p$ and np elastic scattering and from the ρ (dashed) and A_2 (dotted) exchanges for np CHEX (times 20). Also shown are vectors corresponding to the total N_0 amplitude (solid) at this s and t value.
- (h) Same as (g) but for $t = -0.5$ (GeV/c)².
- (i) Same as (g) but for $t = -1.0$ (GeV/c)².

Fig. 8

- (a)-(b) Amplitudes for pp elastic scattering resulting from "Kane Model" at 6.0 GeV/c. The amplitudes are in units of $[mb/(GeV/c)^2]^{1/2}$ and have been multiplied by $e^{-2.5t}$. The amplitude U_0 is assumed to be zero (no " A_1 -type" exchange, see Table 1).

Fig. 9

- (a)-(d) Predictions for the HT-CM (center of mass) observables defined in Table 3 for pp elastic scattering at 6.0 GeV/c resulting from "Kane Model".
- (e)-(f) Predictions for some of the H²-LAB observables defined in Table 3 for pp elastic scattering at 6.0 GeV/c resulting from "Kane Model." These observables are either being measured now or will be measured in the near future. The dotted curves correspond to either $-\cos\phi_R$ or $\sin\phi_R$.

Fig. 10 (a) Experimentally determined values for the transversity differential cross sections (Eq. 4.2) $d\sigma_{++}/dt$, $d\sigma_{+-}/dt$, and $d\sigma_{-+}/dt$ for pp elastic scattering at 6.0 GeV/c compared with the results of "Normal Regge." Also shown are the predicted values of the unnatural parity contribution $d\sigma_{+-}^u/dt$ (dotted curve). (Notice that the vertical scale is not continuous.)

- (b) The same as (a) but for "Regge- ω -flip."
- (c) The same as (a) but for "Regge-Pom-flip."
- (d) The same as (a) but for "Super-Regge."

Fig. 11 (a) Randomly generated transversity amplitudes that produce at $t = -0.1$ (GeV/c)² the P , C_{NN} and D_{NN} values lying within the ranges shown for pp scattering at 6.0 GeV/c. The amplitude T_{++++} is defined to be purely imaginary and we have assumed $T_{+-+} = T_{+--}$ (no " A_1 -like" exchange). Also shown are vectors corresponding to the predictions of "Super-Regge." Notice that although T_{----} and T_{++-} could lie anywhere on the ring the models result in these amplitudes having nearly the same phase as T_{++++} . The predicted magnitude for (T_{++-}) is very small (see Fig. 10 (dotted curve)).

- (b) Same as (a) but at $t = -0.5$ (GeV/c)².
- (c) Same as (a) but at $t = -1.0$ (GeV/c)².
- (d) Same as (a) but for the u-channel helicity amplitudes. Here N_0 is defined to be purely imaginary. Although N_0 could lie within the range shown on the positive imaginary axis, all the models have N_0 near its maximally allowed value.

Fig. 12 (a) Predictions for the phases of the natural parity transversity amplitudes T_{++++} (crosses), T_{----} (diamonds), and T_{+-+} (squares); and the unnatural parity transversity amplitude T_{++-} (dots) resulting from "Regge- ω -flip" for pp elastic scattering at 6.0 GeV/c. Also shown are the relative phases $\delta_1 = T_{----} - T_{++++}$ (diamonds); $\delta_2 = T_{+-+} - T_{++++}$ (squares); and $\delta_3 = T_{++-} - T_{++++}$ (dots). We have assumed $T_{+-+} = T_{+--}$ (no A_1 type exchange contributions).

40.

(b) Same as (a) but for "Regge-Pom-11p."

(c) Same as (a) but for "Kine Model."

(d) Same as (a) but for "Super-Regge." Notice that the relative phases ϕ_1 and ϕ_2 are small for all models; however, "Kine Model" and "Super-Regge" predict a different sign for ϕ_1 .

Fig. 1 (c)

Fig. 1 (d)

FIG. 1 (a)

FIG. 1 (b)

Fig. 2 (b)

FIG. 3 (a)

Fig. 3 (d)

$p p \rightarrow p p$ Field-Stevens Regge- ω -flip

Fig. 1 (b)

$\bar{p} p \rightarrow \bar{p} p$ Field-Stevens Regge- ω -flip

Fig. 1 (c)

Fig. 4 (a)

$p p \rightarrow p p$ Field-Stevens Regge-Pom-flip

Fig. 4 (b)

$\bar{p} p \rightarrow \bar{p} p$ Field-Stevens Regge-Pom-flip

Fig. 4 (c)

FIG. 4 (d)

Fig. 5 (a)

Fig. 5 (b)

Fig. 5 (c)

Fig. 5 (d)

Fig. 5 (e)

p p $\rightarrow$ p p Field-Stevens Super-Regge
2 GeV/c 3 GeV/c

FIG. 5 (l)

p p $\rightarrow$ p p Field-Stevens Super-Regge
4 GeV/c 6 GeV/c

FIG. 5 (r)

Fig. 5 (a)

Fig. 5 (b)

n p $\rightarrow$ n p Field-Stevens Super-Regge
2 GeV/c 3 GeV/c

Fig. 5 (j)

n p $\rightarrow$ n p Field-Stevens Super-Regge
4 GeV/c 6 GeV/c

Fig. 5 (k)

FIG. 6 (a)

Field-Stevens Super-Regge

(a, b, c)

Field-Stevens Super-Regge

(d, e, f)

Field-Stevens Super-Regge

FIG. 6 (a)

Field-Stevens Super-Regge

FIG. 6 (b)

Field-Stevens
 $N_0(\text{Total})$

$p p \rightarrow p p$
 $N_1(\text{Total})$

Field-Stevens
 $N_2(\text{Total})$

$p p \rightarrow p p$
 $U_2(\text{Total})$

$\text{Amp} \propto e^{-2.5t} (\text{mb}/(\text{GeV}/c)^2)^{1/2}$
Super-Regge 6 GeV/c

FIG. 7 (a)

$\text{Amp} \propto e^{-2.5t} (\text{mb}/(\text{GeV}/c)^2)^{1/2}$
Super-Regge 6 GeV/c

FIG. 7 (b)

$\text{Amp} \times e^{-2.5t} \text{ (mb/(GeV/c)}^2)^{1/2}$
Super-Regge 6 GeV/c

Fig. 7 (c)

$\text{Amp} \times e^{-2.5t} \text{ (mb/(GeV/c)}^2)^{1/2}$
Super-Regge 6 GeV/c

Fig. 7 (d)

$\text{Amp} \times e^{-2.5t} \text{ (mb/((GeV/c)}^2)^{1/2}$
 Super-Regge 6 GeV/c

Fig. 7 (c)

$\text{Amp} \times e^{-2.5t} \text{ (mb/((GeV/c)}^2)^{1/2}$
 Super-Regge 6 GeV/c

Fig. 7 (d)

Field-Stevens

$P_{lab}=6 \text{ GeV/c}$

$pp \rightarrow pp$

N_0 -Amp

$t=-0.0 \text{ (GeV/c)}^2$

$\bar{p}p \rightarrow \bar{p}p$

Field-Stevens

$P_{lab}=6 \text{ GeV/c}$

$pp \rightarrow pp$

N_0 -Amp

$t=-0.5 \text{ (GeV/c)}^2$

$\bar{p}p \rightarrow \bar{p}p$

$np \rightarrow np$

$np \rightarrow pn$

$np \rightarrow np$

$np \rightarrow pn$

Amp Real $(\text{mb}/(\text{GeV/c})^2)^{1/2}$
Super-Regge 6 GeV/c

Amp Real $(\text{mb}/(\text{GeV/c})^2)^{1/2}$
Super-Regge 6 GeV/c

Amplitude $-2.5t \ (\text{mb}/(\text{GeV}/c)^2)^{1/2}$
Kane-Model

FIG. 9 (a)

Fig. 9 (d)

Fig. 10 (e)

Fig. 11 (b)

Field-Stevens Super-Regge

FIG. 12 (d)

Field-Stevens Kane-Model

FIG. 12 (c)

APPENDIX

BEHAVIOR OF LOW AND MEDIUM ENERGY NN SCATTERING
AND AMPLITUDE RECONSTRUCTION*

G. H. Thomas

High Energy Physics Division
Argonne National Laboratory
Argonne, Illinois 60439

This Appendix summarizes what has been learned about amplitude reconstruction based on NN phase shifts. Also, a discussion is given about how existing and future measurements above the phase shift region can be used to tell us about the amplitudes. Contained here are graphs of s-channel helicity amplitudes derived from phase shift solutions, along with graphs of the predicted values of laboratory observables measurable at the ZGS. Explicit formulas for these observables are given.

*Work performed under the auspices of the U. S. Energy Research and Development Administration.

It is not the purpose of this Appendix to give a comprehensive review of what is a very old field of physics, and so complete references to original work are not given. There exist a number of reviews on the subject which can be consulted¹ as well as previous study group reports, workshops, etc. on polarization physics.² Relevant references to specific subjects and ideas are given in the text below as they come up.

Low Energy Phase Shifts

One constraint on any theory of hadron physics must be the low energy behavior of two body scattering. An interesting example is NN scattering. There are no resonances in the s-channel. Furthermore all four particles carry spin. I presume there is also an historic interest in particular for pp elastic scattering, as it involves the interaction of one of nature's most stable particles. The weak and electromagnetic structure of the nucleon have been extensively probed by electron and neutrino scattering experiments. Elastic scattering of protons on protons probes the strong structure? It would be certainly economic if all of these structures were closely related.

The best summary of low energy NN scattering amplitudes resides in the phase shifts, which have been extracted by several groups³ over the last twenty odd years. This information is most reliable below the inelastic production threshold. Unambiguous phase shifts have been found by Arndt, MacGregor and Wright⁷ for $T \leq 460$ MeV Lab kinetic energy. Although one can produce single pions (above 290 MeV) only one wave is strongly inelastic (1D_2) and these authors claim unique phase shifts in this region. Phase shifts above this region have a declining reliability, and their uniqueness depends somewhat on the theoretical models used to supplement the data.

- 33 -

50145

My purpose is to follow the trend of the different amplitudes from the phase shift regime towards the higher energy regime where many partial waves can contribute, and where the amplitudes show a diffractive behavior. In the latter regime the amplitudes also exhibit rough power law behavior in the c.m. energy $\sqrt{s}$. The power law is conjectured to be related to the quantum numbers in the (t) exchange channel: t is the four momentum transfer. This regime, where simple power law behavior is approximately satisfied can be called the Regge pole region: it is usually conjectured that Regge poles give the lowest order description of this region. It is, of course, expected that in this energy regime there may be important corrections in detail to the Regge pole amplitudes. Also, at higher energies the corrections may become more important, if not actually dominant.

One natural way to express Regge pole amplitudes is in terms of Jacob and Wick⁵ s-channel helicity amplitudes. The notation will be⁶

$$\begin{aligned}\phi_1 &= \langle ++|\phi|++ \rangle \\ \phi_2 &= \langle --|\phi|++ \rangle \\ \phi_3 &= \langle +-|\phi|+- \rangle \\ \phi_4 &= \langle +-|\phi|+- \rangle \\ \phi_5 &= \langle ++|\phi|+- \rangle ;\end{aligned}\quad (1)$$

the normalization is such that

$$\begin{aligned}\sigma_{\text{tot}} &= \frac{2\pi}{k} \text{Im}[\phi_1(0) + \phi_3(0)] \\ \frac{d\sigma}{d\Omega} &= \frac{\pi}{k^2} \frac{1}{2} \left\{ |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2 \right\}\end{aligned}\quad (2)$$

The discussion of the corrections to Regge poles is often given in terms of these amplitudes. It will be convenient sometime to use amplitudes which, at large s and small t , have definite t-channel quantum numbers:⁷

$$\begin{aligned}N_0 &= \frac{1}{2}(\phi_1 + \phi_3) \\ N_1 &= \phi_5 \\ N_2 &= \frac{1}{2}(\phi_4 - \phi_2) \\ U_0 &= \frac{1}{2}(\phi_1 - \phi_3) \\ U_2 &= \frac{1}{2}(\phi_4 + \phi_2) .\end{aligned}\quad (3)$$

N and U denote natural and unnatural parity amplitudes respectively: the subscript denotes the amount of t-channel helicity flip. The observables for NN scattering are given in Table I.⁸ [The notation is $\eta = U_2$ and $A = U_0$ since these amplitudes have π -like and A_1 -like quantum numbers respectively.]

The experimental phase shifts reflect a parametrization of the scattering amplitude in the spin basis. There is a rotation involved in going from one basis to another, which is given in many places. Taking this rotation into account, the (s-channel) helicity partial waves defined by

$$\langle \mu\lambda|\phi|p\sigma \rangle = \frac{1}{2ik} \sum_J (2J+1) T_{\mu\lambda p\sigma}^J \phi_{p-\sigma, \mu-\lambda}^J \quad (4)$$

are given in terms of the spin partial waves by the expressions⁹

$$\begin{aligned}T_1^J &= R_J + \frac{J+1}{2J+1} R_{J+1,J} + \frac{J}{2J+1} R_{J-1,J} + \frac{2\sqrt{J(J+1)}}{2J+1} R^J \\ T_2^J &= -R_J + \frac{J+1}{2J+1} R_{J+1,J} + \frac{J}{2J+1} R_{J-1,J} + \frac{2\sqrt{J(J+1)}}{2J+1} R^J \\ T_3^J &= R_{JJ} + \frac{J}{2J+1} R_{J+1,J} + \frac{J+1}{2J+1} R_{J-1,J} - \frac{2\sqrt{J(J+1)}}{2J+1} R^J\end{aligned}$$

$$T_4^J = -R_{JJ} + \frac{J}{2J+1} R_{J+1,J} + \frac{J+1}{2J+1} R_{J-1,J} - \frac{2\sqrt{J(J+1)}}{2J+1} R^J$$

$$T_5^J = -\frac{\sqrt{J(J+1)}}{2J+1} [R_{J+1,J} - R_{J-1,J}] + \frac{R^J}{2J+1} \quad (5)$$

The notation T_i is analogous to ϕ_i in (1). The general forms of the spin partial waves as used by Arndt, et al.⁴ are

$$\begin{aligned} \text{singlet} \quad R_J &= \cos \rho_J e^{2i\delta_J} - 1 \\ \text{triplet} \quad \begin{cases} R_{JJ} &= \cos \rho_{JJ} e^{2i\delta_{JJ}} - 1 \\ R_{J\pm 1,J} &= \cos \rho_{\pm J} \cos 2\epsilon_J e^{2i\delta_{\pm J}} - 1 \\ R^J &= i \sin 2\epsilon_J e^{i(\delta_{+J} + \delta_{-J} + \alpha_J)} \end{cases} \end{aligned} \quad (6)$$

The inelasticity parameters are ρ_J , ρ_{JJ} , $\rho_{\pm J}$ and α_J . For $I=1$ partial wave amplitudes R_J , $R_{J\pm 1,J}$, R^J are non-zero only for even J ; R_{JJ} only for odd J . For $I=0$ amplitudes odd and even are interchanged. For convenience, the relation of the parametrization (6) to that used by Hoshizaki, et al.¹⁰ is given in Table II.

In order to use the experimental phase shifts to reconstruct the amplitudes, one needs two more pieces of information: 1) the high partial waves are given by one pion exchange (OPE) and 2) pp scattering is corrected for Coulomb scattering.

The OPE amplitudes are⁹

$$\begin{aligned} \phi_2^{\text{OPE}} &= \frac{g^2}{4\pi} \frac{1}{4E} \left\{ c_2 \frac{1+z}{z_0+z} + c_1 \frac{1-z}{z_0-z} \right\} \\ \phi_3^{\text{OPE}} &= \frac{g^2}{4\pi} \frac{1}{4E} c_2 \frac{1+z}{z_0+z} \\ \phi_4^{\text{OPE}} &= \frac{g^2}{4\pi} \frac{1}{4E} c_1 \frac{1-z}{z_0-z} \end{aligned} \quad (7)$$

where $z = \cos \theta$, θ is the c.m. scattering angle, $E = \sqrt{s}/2$, $g^2/4\pi = 14.43$ is the πN coupling constant, $z_0 = 1 + \frac{\mu^2}{2k^2}$, μ is the pion mass, $k^2 = E^2 - M^2$, and M is the proton mass. Here c_1 , c_2 depend on the reaction. For $pp \rightarrow pp$, $c_1 = c_2 = 1$; for $np \rightarrow np$, $c_1 = -1$ and $c_2 = 2$; for $np \rightarrow pn$, $c_1 = 2$ and $c_2 = -1$. The full amplitude consists of the partial wave contributions (5) to the sum (4) plus the full OPE contribution (7) minus the individual OPE partial wave contribution for each J that one fits to an experimental wave. The OPE helicity partial waves are¹¹

$$\begin{aligned} T_2^J &= ik \frac{g^2}{4\pi} \frac{1}{E} \left\{ \delta_{J,0} + (1 - z_0) Q_J(z_0) \cdot \left[\frac{c_1 + (-)^J c_2}{2} \right] \right\} \\ T_4^J &= -ik \frac{g^2}{4\pi} \frac{1}{2E} c_1 \left\{ Q_J(z_0) - \frac{J}{2J+1} Q_{J+1}(z_0) - \frac{J+1}{2J+1} Q_{J-1}(z_0) \right\} \\ T_3^J &= \frac{c_2 (-)^J}{c_1} T_4^J \end{aligned} \quad (8)$$

where $Q_J(z_0)$ is the Legendre polynomial of the second kind:

$$Q_J(z_0) = \frac{1}{2} \int_{-1}^1 dz \frac{P_J(z)}{z_0 - z}$$

$$= \frac{\sqrt{\pi}}{2^{J+1}} \frac{\Gamma(J+1)}{\Gamma(J+\frac{3}{2})} \frac{1}{z_0^{J+1}} F\left(1 + \frac{J}{2}, \frac{1}{2} + \frac{J}{2}, J + \frac{3}{2}, \frac{1}{z_0}\right) \quad (9)$$

Here F is the hypergeometric function, and can be numerically evaluated by power series. The procedure outlined here insures that OPE is added only to the high partial waves which are not fit by the phase shifts.

The Coulomb corrections to the pp elastic phase shifts similarly involve adding a function to each of the ϕ_i , and modifying each of the partial wave amplitudes R that are included in the fit. The partial wave amplitudes are modified as follows:¹²

$$\begin{aligned}
 R_J &\rightarrow R_J e^{2i\phi_J} \\
 R_{JJ} &\rightarrow R_{JJ} e^{2i\phi_J} \\
 R_{J\pm 1, J} &\rightarrow R_{J\pm 1, J} e^{2i\phi_{J\pm 1}} \\
 R^J &\rightarrow R^J e^{i(\phi_{J+1} + \phi_{J-1})}
 \end{aligned} \quad (10)$$

where

$$\begin{aligned}
 \phi_0 &\equiv 0 \\
 \psi_J &= \sum_{m=1}^J \tan^{-1} \left(\frac{f_m}{F} \right) \\
 n &= \frac{1}{137} \frac{E_{Lab}}{F_{Lab}}.
 \end{aligned} \quad (11)$$

To the helicity amplitudes t_i are added the following functions:

$$\begin{aligned}
 \phi_1^c &= \frac{1}{2} [f_c(z) + f_c(-z)] + \frac{z}{2} [f_c(z) - f_c(-z)] \\
 \phi_2^c &= \frac{1}{2} [f_c(z) + f_c(-z)] + \frac{z}{2} [f_c(z) - f_c(-z)] \\
 \phi_3^c &= \frac{1+z}{2} [f_c(z) - f_c(-z)] \\
 \phi_4^c &= \frac{1-z}{2} [f_c(z) - f_c(-z)] \\
 \phi_5^c &= -\frac{\sqrt{1-z^2}}{2} [f_c(z) - f_c(-z)]
 \end{aligned} \quad (12)$$

where

$$f_c(z) = -\frac{n}{K(1-z)} \exp \left[-i \pi \ln \left(\frac{1-z}{2} \right) \right] \quad (13)$$

Example:

The first question one may study is the reason behind the observed large value of $\sigma_{++}^{\text{total}} - \sigma_{ij}^{\text{total}}$. Here $\sigma_{ij}^{\text{total}}$ is the total cross section measured with a proton beam polarized i along the normal, scattering off of a target polarized j along the normal. The arrows denote alignment (+) or non-alignment (-) with the normal.

The cross section difference, as measured¹³ at the ZGS at 2-6 GeV/c, is positive and of order 10 mb. The information it gives is

$$\Delta\sigma_T = \sigma_{++}^{\text{total}} - \sigma_{+-}^{\text{total}} = -\frac{4\pi}{k} \text{Im}\phi_2(0). \quad (14)$$

There are no large Regge pole contributions to $\text{Im}\phi_2$. The dominant poles are P (Pomeron), f , ω , ρ , A_2 , π and possibly B . S -channel helicity conservation of the Pomeron forbids P contribution to ϕ_2 ; the secondaries f , ω , ρ , A_2 should give approximately real amplitudes if there is rough exchange degeneracy. The pion trajectory gives mostly a real contribution. Thus there is a problem in guessing the origin of the large contribution to ϕ_2 . [The B trajectory is not expected to give such a large contribution.]

We will now show that the origin of the effect may be directly related to the opening of the inelastic channel $pp \rightarrow N\Delta$.¹⁴ A model for $N\Delta$ production was calculated by Mandelstam many years ago.¹⁵ When the $N\Delta$ channel opens, we may take $N\Delta$ to be in an s -wave, so the state is positive parity and total angular momentum is either 1 or 2. The initial pp state, having positive parity must have symmetric spatial wave function and hence antisymmetric spin $S = 0$. It then follows that the only possible initial state is 1D_2 . Thus the $N\Delta$ channel contributes to the inelasticity of only the 1D_2 partial wave. The magnitude is also fixed by Mandelstam. The calculated inelasticity agrees well with that found from the phase shift solutions.¹⁰

The 1_{D_2} wave contributes only to ϕ_1 and ϕ_2 (equal and opposite in sign at $t = 0$). Thus $\Delta\sigma_T$ is a sensitive way of observing its effect. The contribution of the 1_{D_2} wave to $\Delta\sigma_T$ is

$$(\Delta\sigma_T)_{1_{D_2}} = \left(\frac{2\pi}{k^2} \right) (5) (1 - \cos \rho_2 \cos 2\delta_2) \quad (15)$$

where δ_2 is the elastic phase shift, and ρ_2 is the inelastic phase shift.

At 750 MeV (lab) kinetic energy, $\delta_2 = 9.5^\circ$ and $\rho_2 = 60^\circ$. This gives $(\Delta\sigma_T)_{1_{D_2}} = 18.3$ mb. Note if ρ_2 were zero, then the contribution would be 1.9 mb, an order of magnitude smaller due to the small value of the elastic phase shift. One can also check that other contributions to $\Delta\sigma_T$ are small, so the value of $\Delta\sigma_T$ is governed by (15).

A summary of $\Delta\sigma_T$ as computed from phase shift solutions along with the ZGS measurements is given in Fig. 1 and Fig. 2a. Since $\text{Im} f_1$ also receives the same large contribution from 1_{D_2} , another interesting quantity to measure is the total cross section difference for beam and target polarizations anti-aligned with the beam direction versus aligned:

$$\begin{aligned} \Delta\sigma_L &= \sigma_{\perp}^{\text{total}} - \sigma_{\parallel}^{\text{total}} \\ &= \frac{4\pi}{k} \text{Im}[\phi_1(0) - \phi_3(0)]. \end{aligned} \quad (16)$$

The 1_{D_2} contribution is

$$(\Delta\sigma_L)_{1_{D_2}} = \left(\frac{2\pi}{k^2} \right) (5) (1 - \cos \rho_2 \cos 2\delta_2). \quad (17)$$

The experimental $\Delta\sigma_L$ taken from phase shifts is given in Fig. 2b. There is a difference in behavior between $\Delta\sigma_L$ and $\Delta\sigma_T$ due to there being other large

contributions to $\Delta\sigma_L$ coming from the elastic phase shifts, contributions which are large and opposite in sign.

In high energy language we expect ϕ_1 and ϕ_3 to get roughly equal contributions from natural parity exchanges, the dominant contribution coming from Pomeron exchange. The unnatural parity contributions would come from A_1 (and its opposite signature partner) and is usually assumed to be negligible in the NN system. The fact one is getting such a large low energy unnatural parity amplitude may be a surprise.¹⁴

Restriction of Amplitudes by Polarization Data Above the Phase Shift Region

For a system such as NN-NN where all particles carry spin, there is a purely technical problem of determining which pieces of experimental (and theoretical) information are independent and/or consistent. For any system described by m independent complex amplitudes there are m^2 linearly independent observables which depend non-linearly on $2m - 1$ real parameters (the overall phase is not determined). We need 1) a practical way of knowing with any measured subset of the possible observables that the non-linear constraints are being satisfied; 2) the most economical summary of the independent information represented by these observables; 3) a practical way of deciding which observables would best add new independent information consistent with the expected errors of each type of measurement.

To my knowledge no general analytic solution of the above problem exists in the literature.¹⁶⁻¹⁷ As a way of attacking this problem I propose the following computer analysis. To insure that the non-linear constraints will always be satisfied (question (1) above), one generates by simple Monte Carlo a set of the $2m-1$ real independent parameters, from which one can compute all the observables bilinear in the amplitudes. Usually one

or more of the measured observables will be in conflict with the generated value. Whenever this is the case, the set of parameters generated is thrown out. Note one can also impose theoretical constraints on the amplitudes if one wishes, in order to assess what one really knows about the scattering process. Whenever all constraints are satisfied, the generated amplitude is saved in a "map" showing the allowed values. This map is clearly a hypersurface which represents our ignorance about the scattering and answers question (2) above.

The third step in the analysis is to reduce the area of the hypersurface as much as possible (eliminate our ignorance) by performing additional experiments. Although any independent experiment will in principle help, not all are equally effective. In $\pi\pi$ scattering for example, the non-linear constraints between P , R , A are just quadratic: $P^2 + R^2 + A^2 = 1$. For $P \approx 0$, we may have $|R|$ or $|A|$ near unity. Given a crude measurement that determines for example that one is large, the most effective way to reduce the errors on the amplitudes is to do a precision measurement of the remaining small observable. [Cf. Fox¹⁸ for a related discussion of using Monte Carlo methods to study the effect of experimental errors on amplitude determination.]

In the general case where the form of the constraint equations are more complicated and possibly not known, the task of finding the most effective measurements is much harder. Fortunately, there are outside constraints. Experimentally there are typically a few feasible measurements one can imagine doing (q.v. Table I, II, and III). In this case one can study the effectiveness of each as follows. Pick a few typical values for two of the candidate observables, and assign an error which one hopes to achieve. For each value, compute the "map" and compare with the corresponding map based on known

measurements. A similar program is carried out for each candidate. One now has a basis of comparison for the different possible measurements: The measurement which reduces the hypersurface the most is to be preferred. A fortiori, it will give the least ambiguities for the amplitudes.

$$pp \rightarrow pp; P_{Lab} = 6 \text{ GeV}/c; 0.2 \leq \tau \leq 0.5 \text{ GeV}/c^2$$

To illustrate the general plan outlined above, we give the present status of the amplitude maps for $pp \rightarrow pp$ at 6 GeV/c and $0.2 \leq \tau \leq 0.5 \text{ GeV}/c^2$. There exist six measurements to date: $\frac{d\sigma}{dE}$, P , C_{NN} , D_{NN} , K_{NN} and R . In this case the first five, in fact, suffice to determine analytically magnitudes of the five amplitudes

$$\begin{aligned} \langle ++|\psi|++ \rangle &\equiv \psi_1 = U_0 + U_2 \\ \langle ++|\psi|+- \rangle &\equiv \psi_2 = U_0 - U_2 \\ \langle ++|\psi|+- \rangle &\equiv \psi_3 = N_0 + N_2 \\ \langle ++|\psi|+- \rangle &\equiv \psi_4 = (N_0 - N_2) - 2iN_1 \\ \langle ++|\psi|+- \rangle &\equiv \psi_5 = (N_0 - N_2) + 2iN_1 \end{aligned} \quad (18)$$

which are transversity amplitudes. In terms of measured quantities

(u. units) $(1(0,0; 0,0) = 1)$

$$\begin{aligned} |\psi_1|^2 &= \frac{1}{2}(1 - D_{NN} + C_{NN} - K_{NN}) \\ |\psi_2|^2 &= \frac{1}{2}(1 - D_{NN} - C_{NN} + K_{NN}) \\ |\psi_3|^2 &= \frac{1}{2}(1 + D_{NN} - C_{NN} - K_{NN}) \\ |\psi_4|^2 &= \frac{1}{2}(1 + D_{NN} + C_{NN} + K_{NN}) + 2P \\ |\psi_5|^2 &= \frac{1}{2}(1 + D_{NN} + C_{NN} + K_{NN}) - 2P \end{aligned} \quad (19)$$

In practice one has only to generate four relative phases in order to get a possible set of amplitudes. The R measurement imposes one constraint,

so we expect the "map" to be a 3-dimensional hypersurface in the 9 (real) dimensional parameter space of amplitudes. For display purposes we present only the two dimensional projections of the real and imaginary parts of the helicity amplitudes U_0, U_2, N_0, N_1, N_2 . As usual with such projections, it should be noted that some useful information may be lost.

The experimental values used are $\sigma = 1$ (the spin parameters are normalized to the cross section), $P = 0.12 \pm 0.01$, $C_{NN} = 0.10 \pm 0.02$, $K_{NN} = 0.14 \pm 0.08$ and $U_{NN} = 0.95 \pm 0.08$. The actual values for these are generated by Monte Carlo around their central value, with a spread given by the error. The last quantity is R which experimentally follows

$$R \sim -\cos\theta_R \quad (20)$$

which is strongly t dependent. We therefore perform our analysis at a fixed t . We take $-t = 0.3$, for our illustration. The projection of our map is given in Figure 3.

The phase of N_0 is chosen arbitrarily to be $\pi/2$. One can see the possible relative phases of each of the remaining amplitudes. The data show that U_0 and U_2 are small, but not yet well pinned down in magnitude. A surprising feature is that N_0 is not well determined in magnitude, though in principle an accurate measurement of R would test the prejudice that $|N_0| \gg |N_2|$.

We next show how sensitive this map of experimentally possible values is to the measurement $(sn; Os)$. The allowed range of $(sn; Os)$ is roughly -0.50 to 0.50 . Figure 4 shows that the extreme choice of 50% would lead to a highly constrained set of amplitudes. Contrarily, a medium choice (Fig. 5) of 15% shows very little new information on these projections. The conclusion would be that $(sn; Os)$ is not guaranteed to yield new results, though under special circumstances it could.

One can play the same game with other possible observables, to get a model independent idea of their effectiveness. Since $(sn; Os)$ is already measured (but not analyzed) we have taken as an example the situation of that $(sn; Os)$ gives little information as in Fig. 5, and imagined the observables $(ss; Os)$, $(s0, Os)$, $(ns; Os)$ and $(Os; Os)$ were to take non-extreme allowed values. In fact, the effect of adding each of these in order was studied, but we present only one possible set of values. Figure 6 shows that the map of the amplitudes can be drastically reduced in size. The addition of $(s1; Os)$ and $(n1; Os)$ even further reduces the islands of ambiguities. This example shows that with some prior thought, it is in practice possible to obtain a complete set of amplitudes using measurements possible at the ZGS. The smallest set clearly depends on the values the amplitudes actually take (cf. Figs. 4 and 6).

Analytic Reconstruction of Amplitudes

It is important at some stage to be able to use analytic methods¹⁶ in reconstructing the islands discussed above. Work in this direction has been started by DeBoer and Soffer¹⁷. These analytic results agree with the results summarized in Fig. 3 for the islands based on the known measurements.

Phase Shift Amplitudes and Spin Parameters

For purposes of reference, phase shift solution amplitudes are collected here. In doing experiments at the ZGS, some measurements will overlap the phase shift region and so the phase shift solutions for observables can be directly compared and the features directly traced to characteristics of the amplitudes. It is also hoped that the phase shift amplitudes will be a useful constraint on models constructed to describe the spin measurements carried out in the ZGS energy regime.

Figure 7 summarizes the amplitudes for pp elastic scattering at 4 of the energies where phase shift analyses have been performed. The Coulomb corrections have been removed [put $\phi_J = 0$ in (10) and $f_c = 0$ in (12)]. The two lower energies are considered to be unique, whereas the two higher energies represent in each case, one of two possible solutions. Moreover the higher energy solutions involve more model dependent assumptions. Nevertheless, both pairs of solutions at the higher two energies show the same basic trends, and perhaps can be taken as good guides for the amplitudes.

As a comparison to these pp amplitudes, the corresponding observables are also given. We include the Coulomb corrections in the plots below. Fig. 8 summarizes the four spin measurements of the type recently performed at the ZGS: P_0 , C_{NN} , D_{NN} , K_{NN} . Here the target and beam are polarized normal to the production plane. The low energy behavior is qualitatively similar to that as measured at the ZGS.

For measurements involving s or l spins for the recoil particle, the laboratory observables involve rotations of θ_R of the helicity observables. For example Regge theory has simple predictions for $\langle 0x; 0x \rangle \approx 1$ and $\langle 0z; 0x \rangle \approx 0$ at high energies (cf. Fig. 9a and 9b). These quantities are not, however, directly measured.

The next quantities to be measured at the ZGS are $\langle s0; 0s \rangle$ and $\langle sn; 0s \rangle$. The phase shift values are given in Figs. 9b and 9c. Once there is a polarized R/A target, one can measure the quantities plotted in Figs. 10-11.

All of the discussion here has centered on pp elastic scattering. This is only for purposes of illustration of the ideas and techniques. It is to be emphasized that one should be measuring amplitudes for the entire NN - NN system. Therefore the phase shift solutions at one energy will also be given below. The new ingredients are the $I = 0$ phase shifts. At the

chosen energy the solution is claimed to be unique; I know of no solutions at higher energies at present which have the same claim of reliability.

The amplitudes for np elastic scattering and np CEX, with no Coulomb corrections, are given in Fig. 12. The corresponding observables, with no Coulomb corrections, are given in Figs. 13-16

SUMMARY

Phase shift solutions above the inelastic threshold have been used to illustrate the behavior of NN amplitudes and observables. Such solutions should be interpreted with restraint. Since the inelasticities are very poorly known, predictions for observables which depend on the magnitudes of the inelasticities may be wrong. Predictions for the two total cross sections $\Delta\sigma_T$ and $\Delta\sigma_L$ are examples of observables whose values are sensitive to the inelastic phases. It is therefore very worthwhile to measure these quantities in the region 1 - 2 GeV/c where there is an overlap with phase shift solutions.

More generally, if one proposes to measure a certain observable at the ZGS, one should check to see how well predicted this quantity is from phase shifts. If it is poorly known, measurements in the 1 - 2 GeV/c range could be contemplated. In this appendix enough details about the relationship between observables and phase shifts have been given to allow one to carry out such a calculation.

For the higher energy regime above the phase shift region, we have emphasized how one can check whether a new measurement will yield new information about the amplitudes. In any amplitude analysis, this is certainly a necessary step. In deciding whether or not to do the experiment, one should be guided also by a concern for what might be not

only new, but theoretically interesting. This is treated elsewhere in the present report. (See for example the "picture book" of Field and Stevens).

ACKNOWLEDGEMENTS

I am indebted to my colleagues for their help with this Appendix. Particular thanks to A. Yokosawa for providing Figs. 3-6. Also to E. Berger and T. Fields for constructive discussions.

REFERENCES

1. M. H. MacGregor, M. J. Moravcsik, and H. P. Stapp, *Ann. Rev. Nucl. Sci.* 10, 291 (1960); 10, 325 (1960). International Conference on the Nucleon Nucleon Interaction, Editors A. E. S. Green, M. H. MacGregor and R. Wilson, *Rev. Mod. Phys.* 39, 495 (1967).
2. 11th International Conference on Polarized Targets, G. Shapiro ed., (National Technical Information Service, U.S. Department of Commerce, Virginia, 1971). ZGS Workshops, Summer 1971, T. A. Ramanowski ed., *ANL/HEP-7208*, Vol. III; Proceedings of the Symposium of the High Energy Physics of Polarized Beams, *ANL/HEP 7440*; Proceedings of the Summer Studies on High Energy Physics with Polarized Beams, *ANL/HEP 75-02*.
3. See [1]. For notation and conventions, see also H. P. Stapp, T. J. Ypsilantis and N. Metropolis, *Phys. Rev.* 105, 302 (1958).
4. R. A. Arndt, M. H. MacGregor and R. M. Wright, *Phys. Rev.* 182, 1714 (1969); 173, 1272 (1968); 169, 1149 (1968).
5. M. Jacob and G. C. Wick, *Ann. Phys.* 7, 404 (1959).
6. M. L. Goldberger, M. T. Grisaru, S. N. MacDowell and D. Y. Wong, *Phys. Rev.* 120, 2250 (1960).
7. E. Leader and R. C. Slansky, *Phys. Rev.* 148, 1491 (1966).
8. F. Halzen and G. H. Thomas, *Phys. Rev.* D10, 344 (1974).
9. A. Scotti and D. Y. Wong, *Phys. Rev.* 138, B145 (1965).
10. N. Hoshizaki and T. Kadota, *Prog. Theor. Phys.* 42, 815-826 (1969); N. Hoshizaki, T. Kadota and K. Maki, *Prog. Theor. Phys.* 45, 1123 (1971).
11. See, MacGregor, Moravcsik and Stapp, Ref. 1. Note on page 341 of this reference, there is a sign error in the expression for σ^J for the term Q_{J-1} : should be $Q_{J+1} + Q_{J-1} - 2Q_J$.

12. See, Stapp, Ypsilantis and Metropolis, Ref. 3.
13. W. DeBoer, et al., Phys. Rev. Letters 34, 558 (1975).
14. G. L. Kane and G. H. Thomas,
ANL-HEP-PR-75-56.
15. S. Mandelstam, Proc. Roy. Soc. A244, 491 (1958).
16. See for example, C. R. Schumacher and H. A. Bethe, Phys. Rev. 121,
1534 (1961); R. Oehme, Phys. Rev. 98, 216 (1955); S. M. Bilenky, L. I.
Lapidus, R. M. Ryndin, Soviet Physics JETP 24, 593 (1957); G. H. Thomas,
Thesis (1969).
17. Private communication, W. DeBoer and J. Soffer, to be issued as
ANL-HEP 75-63
18. G. Fox, Proceedings of the IInd International Conference on Polarized
Targets, G. Shapiro, ed. (LBL 1971) p. 117.

FIGURE CAPTIONS

1. The quantity $\Delta\sigma_T = \sigma_T(++) - \sigma_T(+-) = -\frac{4\pi}{k} \text{Im} p_2(0)$ is plotted for
pp + pp. The phase shift results are from Arndt et al. [4] and Hoshizaki
et al. [10]. The errors are not shown. The points of DeBoer et al. [13]
are taken at the ZGS with the polarized beam.
- 2a. A linear plot of $\Delta\sigma_T$ as shown in Fig. 1.
- 2b. The spin correlation total cross section $\sigma_T(\vec{s}) - \sigma_T(\vec{s}') = \frac{4\pi}{k}$
 $\text{Im}[\phi_1(0) - \phi_3(0)]$ as would be measured with longitudinally polarized
beam on longitudinally polarized target. The points are from phase
shifts [4, 10].
3. A map of allowed regions for the pp elastic amplitudes (see text) is
shown as the shaded regions, using as constraints nominal values for
the measured experimental observables: $P = 0.12 \pm 0.01$; $C_{NN} = 0.10 \pm 0.02$,
 $K_{NN} = 0.14 \pm 0.30$; $D_{NN} = 0.95 \pm 0.08$; $R = -0.30 \pm 0.20$.
4. As in Fig. 3, but with the pseudo-data $(sn; Os) = 0.50 \pm 0.08$.
5. As in Fig. 3, but with the pseudo-data $(sn; Os) = 0.15 \pm 0.08$.
6. As in Fig. 3, but with the pseudo-data $(sn; Os) = 0.15 \pm 0.08$;
 $(ss; 00) = -0.15 \pm 0.02$; $(ns; Os) = -0.72 \pm 0.08$; $(Os; Os) = -0.40 \pm 0.08$;
 $(s0; Os) = 0.15 \pm 0.08$. This gives the shaded regions for the amplitudes.
In addition if one adds the pseudo-data $(s1; 00) = -0.05 \pm 0.02$ and
 $(n1; Os) = 0.55 \pm 0.08$ one obtains the dark area for the amplitudes.
The choice of the pseudo-data was based on taking non-extreme values
of the parameters, analyzing the amplitude after the addition of each
parameter to those discussed in Fig. 3.
7. Shown are the phase shift amplitudes [4, 10] for pp + pp in units
of $\sqrt{\text{mb/GeV}/c^2}$. The normalization is such that the sum of squares
gives $\frac{d\sigma}{dt}$; i.e. we plot real and imaginary parts of

$$\sqrt{0.389 \frac{\pi}{2k^2}} \phi_1(t).$$

The 4 energies are 400, 750, 970 and 1400 MeV kinetic energy, or equivalently 0.955, 1.404, 1.662 and 2.142 GeV/c lab momentum. Shown by an arrow is the $\theta_{cm} = 90^\circ$ point for each energy. The Coulomb corrections (10, 12) are not included. Finally note that at the two higher energies, the solutions are not unique. Only one of the two possible solutions (Sol. A) in each case is shown. These amplitudes are interesting benchmarks to compare high energy models to.

8. Here are shown the parameters for $pp \rightarrow pp$ involving a target polarized normal to the production plane corresponding to the amplitudes of Fig. 7. Coulomb corrections are here included in these amplitudes. The 90° point is noted by an arrow.
9. (a) Here are shown two parameters for $pp \rightarrow pp$ which are not measured in standard set ups but have simple Regge predictions at high energies.
(b) The parameters for $pp \rightarrow pp$ which require a solenoid for the beam; the amplitudes are those of Fig. 7 with Coulomb corrections added.
10. As in Fig. 8 for parameters with an R/A target polarized along s.
11. As in Fig. 8 for parameters with an R/A target polarized along l.
12. The phase shift amplitudes, normalized as in Fig. 7, for $np \rightarrow np$ and $np \rightarrow pn$ at $T = 750$ MeV ($P_{Lab} = 1.404$ GeV/c). Coulomb corrections are not included.
13. Here are shown the parameters for $np \rightarrow np$ and $np \rightarrow pn$ involving a target polarized normal to the production plane corresponding to the amplitudes of Fig. 12. Coulomb corrections are not included. The 90° point is denoted by an arrow.
14. (a) As in Fig. 13 for parameters having simple Regge interpretation.
(b) As in Fig. 13 for parameters involving a solenoid to rotate the beam spin along s.

15. As in Fig. 13 for parameters involving target spin along s.
16. As in Fig. 13 for parameters involving target spin along l.

TABLE I. The laboratory observables $f(\text{beam, target, scattered, recoil}) = f(\mu, \delta, \epsilon, d)$ for $NN \rightarrow NN$ are defined with respect to a frame for each particle such that $\hat{z}$ is along the normal to the scattering plane. $\hat{z}$ is along the direction of motion, and $\hat{x}, \hat{y}, \hat{z}$ is in the scattering plane. Since the target is at rest and $\hat{z}$ is undefined, by convention we use for the target the beam unit vectors. θ_1 and θ_2 are the laboratory scattering and recoil angles, respectively. The observables $f(\mu, \delta, \epsilon, d)$ are just those measured with a polarized beam scattering off of a polarized target, with second $\pm$ in terms performed to analyze the polarization of the scattered and recoil nucleon. In general, given the cross sections $\sigma(\mu, \pm, \pm, \pm)$ when each initial particle is polarized and each final particle's polarization analyzed parallel (+) or antiparallel (-) to a given direction $\hat{\mu}, \hat{\delta}, \hat{\epsilon}$, or $\hat{d}$, the ratio of the corresponding observable in the table to the unpolarized cross section is the ratio

$$\frac{\sum_i n_{\mu} n_{\delta} n_{\epsilon} n_d \sigma(n_{\mu}, n_{\delta}, n_{\epsilon}, n_d)}{\sum_i \sigma(n_{\mu}, n_{\delta}, n_{\epsilon}, n_d)},$$

where $n_i = \pm 1$. If an initial particle is unpolarized or a final particle's polarization is not analyzed, delete the corresponding factor n_i and omit the sums over this n_i . The vectors $\hat{x}, \hat{y}$, and $\hat{z}$ denote the center-of-mass helicity-frame directions. Their relationship to μ, δ, ϵ , and d for each particle can be inferred from the table by noting that $f(\mu, \delta, \epsilon, d)$ is linear in its arguments; e.g., $f(\mu, \pm, \pm, \pm) = f(\mu, \pm, \pm, \pm) + f(\mu, \pm, \pm, \pm) + f(\mu, \pm, \pm, \pm)$. The μ, δ, ϵ , and d directions would be appropriate to polarization measurements in a colliding-beam measurement. The exchange amplitudes in the third part of the table are combinations of s -channel helicity amplitudes which asymptotically have definite t -channel quantum numbers. In terms of the usually defined amplitudes, $N_3 = \frac{1}{2}(\phi_1 + \phi_2)$, $N_1 = \phi_1$, $N_2 = \frac{1}{2}(\phi_1 - \phi_2)$, $N_4 = \frac{1}{2}(\phi_1 + \phi_2)$, and $A = \frac{1}{2}(\phi_1 - \phi_2)$.

Laboratory observables	Center-of-mass observables	Exchange amplitudes
$f(0, 0, 0, 0)$	$f(0, 0, 0, 0)$	$[N_1]^2 + 2[N_2]^2 + [N_3]^2 + A ^2$
$f(0, \mu, 0, 0)$	$-f(0, y, 0, 0)$	$-2\text{Im}(N_1 - N_2)N_3^*$
$-f(0, \pm, 0, \pm) \cos \theta_R + f(0, \pm, 0, \pm) \sin \theta_R$	$f(0, \pm, 0, \pm)$	$[N_2]^2 - [N_3]^2 - A ^2$
$f(0, \pm, 0, \pm) \sin \theta_R + f(0, \pm, 0, \pm) \cos \theta_R$	$f(0, \pm, 0, \pm)$	$-2\text{Re}(N_2 + N_3)N_1^*$
$f(0, \mu, 0, \mu)$	$f(0, y, 0, y)$	$[N_2]^2 + 2[N_3]^2 + [N_4]^2 - A ^2$
$-f(0, \pm, 0, \pm) \sin \theta_R - f(0, \pm, 0, \pm) \cos \theta_R$	$f(0, \pm, 0, \pm)$	$[N_2]^2 - [N_3]^2 + A ^2$
$f(0, \pm, 0, 0)$	$-f(0, \pm, 0, 0)$	$-2\text{Re}(N_2 A^* - N_3 A)$
$f(\mu, \pm, 0, 0)$	$-f(\mu, \pm, 0, 0)$	$2\text{Re}(A^* A)N_1^*$
$f(\mu, \mu, 0, 0)$	$-f(y, y, 0, 0)$	$2\text{Re}(A^* A - N_2 N_3^* + [N_1]^2)$
$f(\mu, \mu, 0, 0)$	$f(\mu, \pm, 0, 0)$	$2\text{Re}(N_2 A^* - N_3 A)$
$f(\mu, 0, 0, \mu)$	$-f(y, 0, 0, y)$	$-2\text{Re}(A^* A - N_2 N_3^* - [N_1]^2)$
$f(\mu, 0, 0, \pm) \sin \theta_R + f(\mu, 0, 0, \pm) \cos \theta_R$	$-f(\mu, 0, 0, \pm)$	$-2\text{Re}(N_2 A^* + N_3 A)$
$-f(\mu, 0, 0, \pm) \cos \theta_R + f(\mu, 0, 0, \pm) \sin \theta_R$	$-f(\mu, 0, 0, \pm)$	$-2\text{Re}(A - A)N_1^*$
$f(0, \pm, \pm, 0) \cos \theta_R + f(0, \pm, \pm, 0) \sin \theta_R$	$-f(0, \pm, \pm, 0)$	$-2\text{Re}(N_2 A^* + N_3 A)$
$f(\mu, \pm, 0, \pm) \sin \theta_R + f(\mu, \pm, 0, \pm) \cos \theta_R$	$-f(y, \pm, 0, \pm)$	$2\text{Im}(N_2 + N_3)N_1^*$
$f(\mu, \mu, 0, \pm) \sin \theta_R + f(\mu, \mu, 0, \pm) \cos \theta_R$	$f(y, y, 0, \pm)$	$2\text{Im}(A - A)N_1^*$
$f(\mu, \pm, 0, \mu)$	$-f(y, \pm, 0, y)$	$-2\text{Im}(A^* A)N_1^*$
$f(\mu, \pm, 0, \pm) \cos \theta_R - f(\mu, \pm, 0, \pm) \sin \theta_R$	$f(y, \pm, 0, \pm)$	$2\text{Im}(A^* A - N_2 N_3^*)$
$-f(\mu, \pm, 0, \pm) \cos \theta_R + f(\mu, \pm, 0, \pm) \sin \theta_R$	$f(y, \pm, 0, \pm)$	$2\text{Im}(N_2 A^* + N_3 A)$
$f(0, \mu, 0, \pm) \sin \theta_R + f(0, \mu, 0, \pm) \cos \theta_R$	$f(0, y, 0, \pm)$	$2\text{Im}(N_2^* + N_3^*)$
$f(0, \pm, 0, \mu)$	$-f(0, \pm, 0, y)$	$-2\text{Im}(A^* A - N_2 N_3^*)$
$f(\mu, \pm, 0, \pm) \sin \theta_R + f(\mu, \pm, 0, \pm) \cos \theta_R$	$f(y, \pm, 0, \pm)$	$2\text{Im}(A^* A + N_2 N_3^*)$
$-f(\mu, \pm, 0, \pm) \cos \theta_R - f(\mu, \pm, 0, \pm) \sin \theta_R$	$f(y, \pm, 0, \pm)$	$2\text{Im}(A^* A - N_2 N_3^*)$
$f(\mu, \pm, 0, \pm) \sin \theta_R + f(\mu, \pm, 0, \pm) \cos \theta_R$	$f(y, \pm, 0, \pm)$	$2\text{Im}(A^* A + N_2 N_3^*)$
$f(\mu, \pm, 0, \pm) \sin \theta_R - f(\mu, \pm, 0, \pm) \cos \theta_R$	$f(y, \pm, 0, \pm)$	$-2\text{Im}(N_2 A^* - N_3 A)$
$f(\mu, \pm, \pm, \pm) \sin \theta_R \sin \theta_R - f(\mu, \pm, \pm, \pm) \cos \theta_R \cos \theta_R$	$f(\mu, \pm, \pm, \pm)$	$[N_1]^2 - 2[N_2]^2 + [N_3]^2 + A ^2$
$+f(\mu, \pm, \pm, \pm) \sin \theta_R \cos \theta_R - f(\mu, \pm, \pm, \pm) \cos \theta_R \sin \theta_R$	$f(\mu, \pm, \pm, \pm)$	$2\text{Re}(N_2 - N_3)N_1^*$
$-f(\mu, \pm, \pm, \pm) \sin \theta_R \cos \theta_R - f(\mu, \pm, \pm, \pm) \cos \theta_R \sin \theta_R$	$f(\mu, \pm, \pm, \pm)$	
$+f(\mu, \pm, \pm, \pm) \sin \theta_R \sin \theta_R + f(\mu, \pm, \pm, \pm) \cos \theta_R \cos \theta_R$	$f(\mu, \pm, \pm, \pm)$	

Optical theorem: $\sigma_{\text{tot}} = \frac{4\pi}{k} \text{Im} f(0, 0) = \frac{4\pi}{k} \text{Im} f(0, 0) = \frac{4\pi}{k} \text{Im} f(0, 0) = \frac{4\pi}{k} \text{Im} f(0, 0)$

$$f(0, 0) = \text{Im} N_1, f(\mu, \pm, \pm) = \text{Im} (N_2 - N_3), f(0, \pm) = -\text{Im} A$$

TABLE II

To convert from the notation of Hoshizaki et al. to Arndt et al., use the following, for each J:

Arndt et al.

Hoshizaki et al.

ρ_J

$\cos^{-1} r_J$

ρ_{JJ}

$\cos^{-1} r_{JJ}$

α

ϕ_J

ϵ

$\frac{1}{2} \sin^{-1} \left[\rho_J \sqrt{r_{\pm}^2} \right]$

$\rho_{\pm}$

$\sin^{-1} \left[\frac{\sqrt{1-r_{\pm}^2}}{\cos 2\epsilon} \right]$

TABLE IIIA
GENERAL FORMULA

- 1) $(s \cos \alpha + l \sin \alpha, 0; 0, s \cos \beta + l \sin \beta)$
 $= \cos \alpha \cos(\theta_R - \beta) (x00x) + \sin(\theta_R + \alpha - \beta) (x00z)$
 $+ \sin \alpha \sin(\theta_R - \beta) (z00z)$
- 2) $(s \cos \alpha + l \sin \alpha, n; 0, s \cos \beta + l \sin \beta)$
 $= \cos(\theta_R + \alpha - \beta) (x00x)$
 $+ \cos \alpha \sin(\theta_R - \beta) (xy0z)$
 $+ \sin \alpha \cos(\theta_R - \beta) (zy0x)$
- 3) $(s \cos \alpha + l \sin \alpha, s \cos \beta + l \sin \beta; 0, 0)$
 $= \cos \alpha \cos \beta (xx00) - \sin(\alpha + \beta) (xz00)$
 $- \sin \alpha \sin \beta (zz00)$
- 4) $(s \cos \alpha + l \sin \alpha, s \cos \beta + l \sin \beta; 0, n)$
 $= \cos(\alpha + \beta) (xx0y) - \cos \alpha \sin \beta (xz0y)$
 $+ \sin \alpha \cos \beta (zx0y)$
- 5) $(0, s \cos \alpha + l \sin \alpha; 0, s \cos \beta + l \sin \beta)$
 $= - \cos \alpha \cos(\theta_R - \beta) (0x0x)$
 $+ \sin(\theta_R + \alpha - \beta) (0z0x)$
 $+ \sin \alpha \sin(\theta_R - \beta) (0x0z)$

TABLE IIIA (Cont.)

- 6) $(n, s \cos \alpha + l \sin \alpha; 0, s \cos \beta + l \sin \beta)$
 $= - \cos(\theta_R + \alpha - \beta) (yx0x)$
 $- \cos \alpha \sin(\theta_R - \beta) (yx0z)$
 $+ \sin \alpha \cos(\theta_R - \beta) (y'x'x)$

Note: Standard set ups: choose $\alpha = 0$ or $\pi/2$ and
 $\beta = 0$ or $\pi/2$. Magnetic fields will in general
change these values.

TABLE IIIB
LABORATORY OBSERVABLES

The quantities $(\alpha\beta; \gamma\delta)$ are defined in terms of quantities in Table I: $(\alpha\beta; \gamma\delta) \equiv I(\alpha\beta; \gamma\delta)/I(00; 00)$. Recall that $U_0 \equiv A$ and $U_2 \equiv \pi$. The lab. recoil angle θ_R is given by $\tan\theta_R = \frac{m}{E} \cot \theta/2$ where θ is the c.m. scattering angle, $E = \sqrt{s}/2$ and m is the proton mass. The order of the spin label is (beam, target; scattered, recoil), i.e. $\alpha\beta + \gamma\delta$.

$$P = (0n; 00) = -(0y; 00)$$

$$R = (0s; 0s) = -(0x; 0x)\cos\theta_R + (0z; 0z)\sin\theta_R$$

$$(01; 0s) = (0z; 0z)\sin\theta_R + (0x; 0x)\cos\theta_R$$

$$A = (0s; 01) = -(0x; 0x)\sin\theta_R - (0z; 0z)\cos\theta_R$$

$$(01; 01) = -(0z; 0z)\cos\theta_R + (0x; 0x)\sin\theta_R$$

$$D_{NN} = (0n; 0n) = (0y; 0y)$$

$$(11; 00) = -(zz; 00)$$

$$(s1; 00) = -(xz; 00)$$

$$C_{NN} = (nn; 00) = -(yy; 00)$$

$$(ss; 00) = -(xx; 00)$$

$$K_{NN} = (n0; 0n) = -(y0; 0y)$$

$$(s0; 0s) = -(x0; 0x)\cos\theta_R - (x0; 0z)\sin\theta_R$$

$$(10; 0s) = -(0z; z0)\sin\theta_R - (x0; 0z)\cos\theta_R$$

$$(s0; 01) = -(x0; 0x)\sin\theta_R + (x0; 0z)\cos\theta_R$$

$$(10; 01) = (0z; z0)\cos\theta_R - (x0; 0z)\sin\theta_R$$

$$(ns; 0s) = -(yx; 0x)\cos\theta_R - (yz; 0z)\sin\theta_R$$

$$(n1; 0s) = (yx; 0x)\sin\theta_R + (yz; 0z)\cos\theta_R$$

$$(ns; 01) = -(yx; 0x)\sin\theta_R + (yz; 0z)\cos\theta_R$$

$$(n1; 01) = -(yx; 0x)\cos\theta_R + (yz; 0z)\sin\theta_R$$

$$(sn; 0s) = (xy; 0z)\sin\theta_R + (xy; 0x)\cos\theta_R$$

TABLE IIIB (Cont.)

$$(1n; 0s) = (zy; 0x)\cos\theta_R - (xy; 0x)\sin\theta_R$$

$$(sn; 01) = -(xy; 0z)\cos\theta_R + (xy; 0x)\sin\theta_R$$

$$(1n; 01) = (zy; 0x)\sin\theta_R + (xy; 0x)\cos\theta_R$$

$$(ss; 0n) = -(xx; 0y)$$

$$(s1; 0n) = -(xz; 0y)$$

$$(1s; 0n) = -(zx; 0y)$$

$$(11; 0n) = -(xx; 0y)$$

TABLE IV

TYPICAL VALUES AT $-t = 0.25$ $P_{\text{Lab}} = 2.142 \text{ GeV/c}$

Observable	Phase Shift Value	[Choice in Monte Carlo $P_{\text{Lab}} = 6 \text{ GeV/c}$]
(ss00)	- 18.1%	- $15 \pm 2 \%$
(ns0s)	1.4	- 72 ± 8
(s00s)	13.7	15 ± 8
(0s0s)	- 38.1	- 40 ± 8
(s100)	- 5.5	- 5 ± 2
(n10s)	31.0	55 ± 8
(sn0s)	25.7	15 ± 8
Data at 6 GeV/c		
P	38.9	12 ± 1
C_{nn}	38.2	10 ± 2
K_{nn}	39.4	14 ± 30
D_{nn}	93.8	95 ± 8
($\phi \equiv 1$)

Figure 1

Figure 3

Figure 2

Figure 5

Figure 4

Figure 7

Figure 6

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

July 8, 1975

July 8, 1975

TO: Polarization TAP Participants

FROM: E. L. Berger

ELB

There are three general remarks which I remember making during the TAP meeting, and which perhaps are worth amplifying.

1. Benchmarks in Elastic Processes

It is next to impossible to judge at a glance whether most of the recent polarized beam results are especially significant, because none of us knows what to expect from any reasonably reliable point of view. First, to my knowledge, polarization observables have not been computed at very low energy, although it is often asserted that the NN amplitudes are well known from phase shift analyses, said to be unique below $p_{lab} = 1$ GeV. It might be very instructive to take the phase shifts, reconstruct amplitudes, and compute all the relevant observables. These "phase-shift predictions" could be compared with Argonne data. The comparison should help us to understand better the import of local elastic polarization observables (e.g. their magnitudes, t and s dependences) in the low momentum ($\lesssim 3$ GeV/c) range. I am glad that Yokosawa and Thomas have followed through on this suggestion. They should have results to show us soon.

Second, at higher energies, 4 to 12 GeV/c, there has not been a recent Regge pole (and/or cut) analysis of NN data. Fits done in the late 60's by various people should be modernized, to include the substantially new qualitative understanding of amplitude structure gained since then. In accounting for existing data on the differential cross-sections and polarizations in pp and pp elastic scattering, and np and pp charge exchange processes, we could determine most parameters of a reasonable and simple model. The polarization observables computed therefore could be compared with Argonne data as they become available. Again, the contrasts will be instructive. Obviously I do not expect the models to be "correct", but I expect to learn from their failings. Thomas and I are working on this problem, as is Rick Field.

2. Resonances and Threshold Effects

This section is based on work I did with Geoff Fox years ago. The ideas are still valid, and I refer you to our "ancient works", particularly Fox's paper at the 11th International Conference on Polarization, Berkeley, 1971.

There are an amazing number of threshold enhancements in high-energy physics: such debated objects as the A_1 , A_3 , $N(1400, 1700)$, Q , and L bumps in production processes and the Z^* (Coul Bump) seen in K⁺p elastic scattering. In each case, the enhancement can be interpreted either as a genuine resonance or as a kinematic by-product of a large exchange amplitude that falls with (sub)-energy ($s^{2\alpha\pi-2}$ for the A_1 , $s^{2\alpha\rho-2}$ for the Z^*), and hence peaks near threshold. The interpretations are not equivalent because for both the A_1 and Z^* , a resonance predicts a purely imaginary amplitude, but the exchange forces are dominantly real.

Doubtlessly there are states in pp scattering analogous to the Z^* of K⁺p, e.g. at the $(\delta^{++}n)$ threshold.

The interpretation of threshold enhancements is still uncertain after a multitude of simple cross-section measurements. This distressing situation follows because the main difference between the rival "theories" lies, not in the shape, but rather in the phase of the amplitude. The only logical way to study such effects is by polarization measurements in the relevant exclusive low multiplicity final states. The reactions $NN \rightarrow NN$ and $NN \rightarrow NnN$ ($N\bar{N}$, N^*N) should be investigated in detail from 1 to 3 GeV/c to help answer these questions. This low momentum range in NN scattering is rich, in that the absence (or weakness) of resonance effects means that structure in various partial waves will reflect more clearly dynamics associated with the other singularities of the S-matrix. Valuable new insight into hadron dynamics should come from an examination of how full amplitudes and their partial waves vary as energy is swept through thresholds. We could begin here at ANL at, say, 1 GeV/c, where phase shift solutions are meant to determine amplitudes uniquely, and work up systematically to, say, 3 GeV/c, obtaining an essentially complete determination of pp amplitudes. If we don't do it here now, it may never be done.

3. Inelastic Exclusive Diffraction Dissociation

Exclusive diffractive processes with the lowest multiplicities are among my favorite reactions:

$$\begin{aligned} pp &\rightarrow p(\pi^+\pi^-) \\ np &\rightarrow (p\pi^-)\pi^+ \\ pp &\rightarrow p(p\pi^+\pi^-) \end{aligned}$$

Polarization measurements at 6 GeV/c could be of immeasurable value in helping us to define the similarities and differences in the amplitude structure of elastic and inelastic diffraction. I have just written an ANL Internal Report on this subject to which I refer you for details.¹

ELB:rv

1. Polarization in Inelastic Diffractive Process, ANL-HEP-PR-75-33.

POLARIZATION IN INELASTIC "DIFFRACTIVE" PROCESSES

Edmond L. Berger

High Energy Physics Division
Argonne National Laboratory
Argonne, Illinois 60439

I. INTRODUCTION.

Measurements at NAL and at the ISR have established that the process $pp \rightarrow pX$ (and $\pi p \rightarrow pX$), with small invariant mass of the missing system X , survives asymptotically and provides a cross-section comparable to elastic scattering.¹ The dependence of $d\sigma/dM_X^2$ on energy is relatively slow, again similar to that of σ_{elastic} , and the momentum transfer dependence of $d^2\sigma/dt dM_X^2$ is fairly steep. One can tentatively define this quasi-elastic process, or the "inelastic diffractive excitation" of a proton into a system X of relatively low mass as a separable reaction mechanism whose further properties deserve special investigation. One good way in which to learn more would be to measure polarization effects in inelastic diffraction, as I discuss in some detail below.

Exclusive diffractive processes with the lowest multiplicities are the easiest to examine.¹⁻⁴ Among these we may list:

- $pp \rightarrow p(\pi^+)$; 1(a)
- $\pi p \rightarrow p(\pi^-)p$; 1(b)
- $pp \rightarrow p(\pi^+ \pi^-)$; 1(c)
- and $\pi p \rightarrow (3\pi)p$. 1(d)

The excited system is indicated in parentheses. The cross-section is concentrated at relatively small mass M of this system,²⁻⁴ $M < 2$ GeV, although the excitation spectrum may extend to very high values. Resonances may be present in the data as well as a broad continuum. In analyzing such reactions as effective quasi-two body processes, one usually defines a quasi-elastic differential cross-section in terms of the momentum transfer t to the isolated proton. The cross section is confined sharply to small t values.

Notable contrasts are apparent when the (quasi-elastic) t dependence of $d\sigma/dt$ is compared with that of $d\sigma/dt$ for elastic scattering. In elastic scattering at ISR energies,⁵ $d\sigma/dt$ falls in featureless, roughly exponential fashion by over 6 orders of magnitude from its maximum at $t = 0$, before encountering a sharp minimum at $|t| \simeq 1.4$ (GeV/c)². When recast in impact parameter language, these data imply that diffractive elastic scattering is a central process⁵, concentrated about zero impact parameter. In contrast, in inelastic diffraction at small values of excitation mass, M , Fermilab data³ on reaction 1(b) and ISR data² on reaction 1(a) show a dip or at least a break in $d\sigma/dt dM$ at $|t| \simeq 0.2$ (GeV/c)², (after a precipitous fall from the maximum at $t = 0$). A dip at such small $|t|$ implies peripheral structure in impact parameter⁶, with the cross-section peaking at about 1 fermi. Although a break near $|t| \simeq 0.2$ (GeV/c)² had been observed in some lower energy data⁷, below 30 GeV/c, the possibility existed that the effect was a non-asymptotic, non-diffractive phenomenon. The ISR and Fermilab results demonstrate the diffractive nature of the inelastic structure. They compel the conclusion that quasi-elastic scattering is peripheral in impact parameter, whereas elastic scattering is central.

The Deck model⁸ has been used extensively to interpret the production and decay characteristics of non-resonant low mass enhancements in the (πa^0) system in diffraction dissociation reactions of the type

$$ap \rightarrow (a^0 \pi) p.$$

1(e)

Here, a is an incident hadron from the set $K^+, \pi^+, K^0, \bar{K}^0, p, \bar{p}, n$, and so forth. The model has enjoyed a considerable measure of at least qualitative success⁹, although difficulties become apparent in detailed experimental comparisons⁸. In particular, according to the model, the distribution in momentum transfer to the diffractively scattered proton should resemble that for elastic scattering, thus showing no structure at $|t| \simeq 0.2$ (GeV/c)² in reactions 1(a) and 1(b). Faced with this problem, Pirila and I recently undertook a detailed investigation of absorption corrections to the pion exchange Deck model. In Ref. 9, we show that absorption of the expected strength produces significant structure in the momentum transfer distributions, similar to that observed in the data from reactions 1(a) and 1(b). In particular, our differential cross-sections $d\sigma/dt dM$ show a pronounced break, whose position moves to larger $|t|$ as M increases. There are no undetermined parameters in our approach. The agreement we achieve with data supports the Deck interpretation of diffractive threshold enhancements, as well as the necessity for absorptive corrections to the model. The Ref. 9 may be consulted for details. Here I want to draw conclusions relevant to polarization investigations of reactions 1(a) - 1(d) at ANL energies.

II. POLARIZATION

The strongest argument for polarization studies in inelastic diffractive processes is the qualitative one: Namely, the reaction mechanism is important and more should be established about it. Fortunately, the case can be strengthened by pointing to model dependent supporting arguments. Below I argue the case from two points of view, by analogy with elastic scattering and, next, by invoking the specific Deck model of inelastic diffraction.

In studies of elastic scattering at modest energies ($p_{lab} \leq 30$ GeV/c), polarization measurements were found to provide some good insight into the nature of the relevant exchange mechanisms. For example, in $\pi^\pm p$ elastic scattering a pronounced "double-zero" structure of polarization is seen near momentum transfer $t \approx -0.6$ (GeV/c) 2 , and the energy

dependence of polarization is roughly proportional to $1/\sqrt{s}$. To understand both effects, recall that polarization P is given by

$$P \frac{d\sigma}{dt} = \text{Im} (H_{++} H_{+-}^*) \quad (2)$$

where H_{++} and H_{+-} are the nucleon spin non-flip and spin-flip amplitudes, respectively. With H_{++} dominated by a predominantly imaginary diffractive contribution ($H_{++} \approx i f(t)$) we see that $P \approx s^{-1}$. Real part of H_{+-} . For $\pi^\pm p$ scattering, the spin-flip amplitude is given by a ρ exchange term whose structure is

$$H_{+-} \approx s^{a_\rho(t)} [1 - e^{-i\pi a_\rho(t)}] \quad (3)$$

with $a_\rho(t) \approx 0.5 + t$. Consequently we expect

$$P \approx s^{-1/2} (1 - \cos \pi a(t)) f(t). \quad (4)$$

This expression shows the required s dependence, and, so long as $f(t)$ is featureless in t , a double zero structure near $t \approx -0.6$ is predicted (where $a \approx 0$). Thus, the data substantiate the relevance of an exchange model description of elastic scattering, with diffractive and Regge contributions, and they confirm in a very clear fashion our beliefs about the phase structure of ρ Regge exchange as a function of t .

Similar analyses have been made of the polarization seen in pp , $\bar{p}p$ and $K^\pm p$ scattering in the range $0 < |t| < 1$. (GeV/c) 2 . For these reactions, analyses of the data support the important predictions of exchange degeneracy of the Regge exchanges.

Polarization measurements in quasi-elastic processes would be subject to the same type of analyses and thus would help to establish to what extent the dynamics of elastic and quasi-elastic processes differ.

One might begin with the simplest case,

$$a \bar{p} \rightarrow X p \quad (5)$$

with beam $a = \pi^\pm, K^\pm, p$ or $\bar{p}$ impinging on a polarized target. System X is the missing mass, and the recoil proton's momentum is the only quantity measured. As in elastic scattering,

$$P = \frac{d\sigma/dt(\uparrow) - d\sigma/dt(\downarrow)}{d\sigma/dt(\uparrow) + d\sigma/dt(\downarrow)}. \quad (6)$$

Here t is the momentum transfer to the recoil proton. I consider X just as if it were a well defined object in, say, a process with only two bodies in the final state. Of course, P would depend in general on the three variables s , t , and M_X , where M_X is the mass of X ; P should be studied as a function of these three. Relevant energies extend from, say, 4 GeV/c in the ANL range, through the FNAL and SPS range. As a (very) crude estimate of the expected size of P one can take the value of elastic polarization at the same $\sqrt{s}$ or (as discussed below) at $\sqrt{s_{el}} = \frac{1}{2} \sqrt{s}$ quasi-elastic.

I believe the investigation of low-multiplicity exclusive processes would be more rewarding and worth the extra experimental effort required.

III. THE DECK MODEL.

As mentioned in the Introduction, one particular model for exclusive inelastic diffraction, the π exchange Deck model, has been reasonably successful in describing many features of these reactions, including s , t , mass and angular dependences.⁸ However, a crucial assumption of the model, which is that the reactions are a promotion of πN elastic scattering, is not tested. This aspect of the model,

illustrated in the diagram, could be studied very nicely with polarization. As the diagram suggests, the polarization predicted in $\pi^+p \rightarrow A_1^+p$, $pp \rightarrow pn\pi^+$ and $K^+p \rightarrow Q^+p$ should be that seen in the elastic π^+p reaction, whereas the polarization predicted for $\pi^-p \rightarrow A_1^-p$, $K^-p \rightarrow Q^-p$, and $pp \rightarrow (\Delta^{++}\pi^-)p$ is that of π^-p elastic. Owing to the fact that the relevant πN subenergy is lower in the inelastic case than in the elastic reaction, the value of polarization will be larger in the inelastic situation for the same s value (e. g. $P_{\text{inelastic}}(s) \simeq P_{\text{el}}(s/4)$). However, the prediction $P \propto s^{-1/2}$ still holds.

The attached Figs. 3 and 4 illustrate these predictions, and contrast them with expectations based on a resonance interpretation of the threshold enhancements. More quantitative calculations were published by Fox.¹⁰

As a result of absorption, the above Deck model predictions are changed considerably. The ISR and FNAL data have taught us that the Pomeron amplitudes in elastic and inelastic diffraction are very different. If we write the effective Pomeron amplitude in both cases as

$$H_{++} \simeq i s f(t), \quad (7)$$

the differences are contained in the function $f(t)$. In elastic scattering $f(t)$ is featureless in t . In inelastic diffraction,

$$f_{\text{inel}}(t) = (1 - t/t_0),$$

where $t_0 \approx -0.3 \text{ (GeV/c)}^2$. Actually, in our explicit model, Pirila and I find that t_0 is a function of the mass M of the diffractively excited system. As M increases $|t_0|$ moves to larger values. In our model for $ap \rightarrow a^+ \pi p$, the absorption term arises from π scattering of a^+ and p in the final state, as illustrated below.

The structure in t of the effective Pomeron amplitude is reflected in the t dependence of the inelastic polarization. Thus, rather than the positive polarization, with a double-zero near $|t| \simeq 0.6 \text{ (GeV/c)}^2$, discussed above^{10,8} for $pp \rightarrow p(n\pi^+)$, I now expect a change of sign of polarization from positive to negative near $|t| \simeq 0.3 \text{ (GeV/c)}^2$ as $M_{\pi\pi^+}$ is increased. When integrated over $|t|$, the polarization as a function of $M_{\pi\pi^+}$ will also be smaller, owing to this sign change. This may explain the small polarization observed in inclusive reactions $pp \rightarrow pX$ at small M_X . For $pp \rightarrow (\Delta^{++}\pi^-)p$, the polarization should be negative at small $|t|$ and then go positive near $|t| \simeq 0.3 \text{ (GeV/c)}^2$.

The new expectations are illustrated in Fig. 6 as the "absorbed" curves. They are compared with Fox's unabsorbed Deck model calculations.¹⁰

REFERENCES

1. For reviews consult the articles by M. Derrick and A. N. Diddens, in Proceedings XVII International Conference on High Energy Physics, London, 1974, ed. by J. R. Smith.
2. CERN-Hamburg-Orsay-Vienna ISR Collaboration. E. Nagy, et al., CERN report submitted to the 17th International Conference on High Energy Physics, London, July, 1974. ($pp \rightarrow p(n\pi^+)$ at $\sqrt{s} = 23$ to 62 GeV).
3. Northwestern-Rochester-Fermilab Collaboration, J. Biel, et al., reports submitted to the International Conference on High Energy Physics, Palermo, June, 1975 ($np \rightarrow pp\pi^-$ from 50 to 300 GeV/c).
4. Aachen-UCLA-UC Riverside-CERN ISR Collaboration R. Webb, et al., Physics Letters B55, 331 and 336 (1975) ($pp \rightarrow p(p\pi^+\pi^-)$ at $\sqrt{s} = 45$ GeV).
5. U. Amaldi Rapporteurs Report, Aix-en-Provence Conference, 1973, Journal de Physique, C1 (1973), p. 241.
6. N. Sakai and J. N. J. White, Nucl. Phys. B59, 511 (1973), and Lett. Nuovo Cimento 8, 618 (1973). M. Jacob and R. Stroynowski, Nucl. Phys. B82, 189 (1974); G. Kane, Acta. Phys. Pol. B3, 845 (1972).
7. R. M. Edelstein, et al., Phys. Rev. D5, 1073 (1972); J. V. Beaupre, et al., Nucl. Phys. B66, (1973); J. Hanlon, et. al., Vanderbilt report VAND-HEP 74(2); Scandinavian Bubble Chamber Collaboration, unpublished data on $pp \rightarrow p\pi^+$ at 19 GeV/c, as quoted by G. Kane, ibid.
8. For a review and list of references to earlier work, consult E. L. Berger, "A Critique of the Reggeized Deck Model" Argonne report ANL/HEP 7506, Daresbury Study Weekend Series No. 8, Ed. by J. B. Dainton and A. J. G. Hey. E. L. Berger, Phys. Rev. 166, 1525 (1968) and 179, 1567 (1969).
9. E. L. Berger and P. Pirila, "Absorptive Effects in Exclusive Diffraction Dissociation", Phys. Letters B59, 361 (1975), and Phys. Rev. D, December, 1975.
10. G. C. Fox, Phys. Rev. D9, 3196 (1974).

Fig. 6 Absorbed and Unabsorbed pion exchange Deck model expectations for polarization at 6 GeV/c

BERGER-DECK MODEL

RESONANCE

BERGER DECK MODEL

RESONANCE MODEL

Fig. 3. Diagrams illustrating the pion-exchange-Deck model and resonance model interpretations of the N^* (1460) enhancement seen in $(\Delta^{++}\pi^-)$ and $(n\pi^+)$ invariant mass plots (from the reactions $pp \rightarrow pp\pi^+\pi^-$ and $pp \rightarrow pn\pi^+$, respectively). Regge exchanges are indicated. Predictions for recoil (free) proton polarization at 5 GeV/c are given for the two models.

Fig. 4. Diagrams illustrating the Deck model and resonance model interpretations of the $Q(\bar{Q})$ enhancement seen in $K^{*0}\pi^+(\bar{K}^{*0}\pi^-)$ invariant mass plots from $K^+p \rightarrow K^+\pi^+\pi^-p$. Predictions for recoil proton polarization at 5 GeV/c are given for the two models.

50,151

N^* PRODUCTION WITH POLARIZED BEAM

A. B. WICKLUND

Argonne National Laboratory

Argonne, Illinois 60439

This appendix consists of two sections. First we give a survey of possibilities and complications involved in examining N^* production, both diffractive and nondiffractive. Second we set down some purely formal results on the decomposition of observables into more fundamental amplitudes defined by naturality, helicity, and isospin labels.

There is no need to emphasize that inelastic NN interactions, even for single pion production, are complicated. A complete experimental program would consist of measuring all relevant charge states to determine isospin properties and of using polarized beam, polarized target, recoil polarimeter and fast forward polarimeter. We do not propose such a program but merely hope to create a conceptual framework in the belief that a sensible ZGS objective would be to provide detailed, precise data on selected 1 and 2 pion production channels. Such a framework relating spin observables to physics quantities has been unnecessary in the past since most inelastic NN reaction studies have addressed much simpler questions, such as where are the bumps in the mass spectra. Now that the gross features of single and double pion production have been mapped out - rough dependence on incident energy, momentum transfer and N^* mass - it seems likely that advances in our understanding will require precise experiments measuring nucleon polarizations, N^* decay distributions and ultimately, model dependent amplitudes, as a function of the kinematic invariants for different charge states.

I. Survey

At ZGS energies a substantial share of the NN total cross section goes into single and double pion production. We have some hope of describing these processes as quasi-two-body reactions of the type

$$N_p N \rightarrow N^* N \quad (\text{beam fragmentation})$$

$$N_p N \rightarrow NN^* \quad (\text{target fragmentation})$$

where the " N^* " decays into $N\pi$ or $N\pi\pi$. The N^* is a state having definite spin, parity, and isospin, but its "decay phase" need not be Breit-Wigner behaved - elucidation of the phase is one object of polarized beam investigations. Note also that the physics of beam and target fragmentation is different. (See Fig. 1.) Target fragmentation gives information similar to that in elastic polarization experiments - namely spin dependence at the nucleon $\rightarrow$ nucleon vertex. In particular, polarization effects in target fragmentation require the interference of at least two distinct production amplitudes (flip and nonflip), irrespective of which N^* states are produced. In contrast, with a single production amplitude (e.g., pure π or Pomeron exchange), polarization effects can arise in beam fragmentation due to the interference of different N^* partial waves; thus we obtain information about decay phases as distinct from production phases. So we naturally associate spin-parity analysis of N^* 's with beam fragmentation studies, whereas beam and target fragmentation are both needed to disentangle production mechanisms. All of the information from beam and target fragmentation studies, including polarized beam-polarized target spin correlation, is examined in Section II.

Note that polarized target and beam measure both kinds of fragmentation simultaneously, including beam-target correlation. However, one attraction of the polarized beam is that single spin measurements can be made with pure H_2 or D_2 targets. In this case, target fragmentation studies require a vertex detector, and so it is an important practical question whether to go ahead with polarized target experiments or develop a high rate vertex detector.

There are at least three mechanisms for " N^* " production: (1) exchange of Regge poles such as π , B, A_1 , ρ , A_2 , ω , f . . . , (2) Pomeron exchange, presumably producing $J^P \approx \frac{1}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+ \dots$ resonant states, and (3) Deck amplitudes involving π exchange (see Fig. 1). In the case of $NN \rightarrow NN^*$ these can all be present simultaneously because most of the simplifying features of π and K induced reactions are absent. The following complications should be kept in mind:

(1) In order even to separate natural from unnatural parity exchange one has to measure both transverse and longitudinal beam polarization and the polarization components of the nucleon from " N^* " decay. Alternately one can measure the depolarization parameter at the NN vertex with a polarized target and recoil nucleon polarimeter. These experiments are hard and are not likely to provide a statistically precise separation as a function of N^* mass, t, and decay angles.

(2) The NN system does not respect G parity so even and odd exchanges are present simultaneously.

(3) Combining difficulties (1) and (2) we see that even π exchange, which

is an important part of the cross section at ZGS energies, cannot be separated without model dependent analysis.

(4) We already know from πN phase shifts that many different overlapping N^* states (with distinct J^P and isospin) can be produced. Moreover, the nonresonant partial waves may also be produced, as they certainly are in the case of π exchange, so it is not clear that a short list of Breit-Wigner parameters will describe the produced N^* 's. An optimistic situation is illustrated in Fig. 2, where we have calculated the cross section for N^* production from phase shifts assuming that only $\frac{1}{2}^+$, $\frac{3}{2}^-$, $\frac{5}{2}^+$, $\frac{7}{2}^-$. . states with $I = \frac{1}{2}$ are produced by a constant Pomeron exchange. The $\frac{1}{2}^+$ state is buried and (not unlike experimental mass spectra) the N^*1520 and N^*1688 seem to dominate the spectrum. Deck backgrounds and other waves could fill in the valley between the peaks, leaving a mess to be unravelled by spin-parity analysis involving the decay moments and spin correlations.

Thus if we want to isolate the "diffractive" component at ZGS energies it seems useful to understand the Regge contributions, especially π exchange, so that these can be removed. Alternately coherent production of N^* 's off d_2 or He can be used to isolate Pomeron exchange, but only at very small momentum transfers.

Despite the complexity of the NN system there are some advantages compared with meson induced reactions. For one, the πN phase shifts are known even for inelastic channels. Thus amplitude and spin-parity analyses have built-in constraints. However it is not clear in general how to describe the production of nonresonant πN waves, even though their parameters are known

from πN scattering. Second, analogous to diffractive production of A_1 and Ω bumps, one can study diffractive production of $N\pi\pi$ systems. However, diffractive production of much simpler $N\pi$ systems may be equally illuminating, without the complication of 3-body isobar analysis. The 3-body analysis is necessary to measure phases with a pion beam, but with polarized beam these phases can be determined for 2-body πN systems. Conversely, polarization may be used to test the assumptions of isobar analysis in production of $N\pi\pi$ systems and to determine inelastic decay parameters of N^* 's.

The separation of Pomeron production of N^* 's from Deck effects has been discussed for many years. Presumably real N^* 's are produced with resonant phases by the Pomeron on top of some Deck background, just as in $A_1-A_2-A_3$ production by pions. The Deck background is needed to describe gross features of the data, namely the production of broad threshold bumps with relative s-wave in $p-\pi$, $N-\pi$, $\Delta-\pi$, $f-\pi$, $N-p$. . . systems. As noted above, to separate these from genuine resonance production, one would like phase information from polarized beam fragmentation studies. Another kind of test that Berger and Fox proposed is to examine polarization at the target nucleon vertex (e.g., target fragmentation). In the Deck model this polarization depends on whether the N^* (or threshold enhancement) decays into π^- , π^0 , or π^+ , the polarization being from the same mechanism as in π^+p elastic scattering. Production polarization for genuine resonance production cannot depend on the decay products of the resonance, provided one is looking at a pure isospin state (i.e., if N^* 's do not come in $I = \frac{1}{2}$, $I = \frac{3}{2}$ pairs). Now it may be that the Berger-Fox prediction works at ZGS energies because

(1) there is a Deck contribution and (2) the polarization associated with this contribution is large because the relevant $\pi^{\pm}p$ subenergy is small. Pomeron excitation of genuine N^* resonances may also occur but the production polarization associated with this contribution may be small (e.g., from P - p interference), because the relevant energy ($\sqrt{s}$) is larger. If this surmise is correct, then both beam and target fragmentation will be important for separating Deck from diffractive production of N^* 's.

Finally, the Regge contributions derived, for example, from charge exchange N^* and Δ production, are themselves of intrinsic interest. We have mentioned that at ZGS energies we want to be able to remove the π exchange contribution from "diffractive" channels. We would also like to relate these Regge contributions to those in meson reactions and in $np \rightarrow pn$, comparing coupling constants, duality breaking, strength of absorption, etc.

If one understands the charge exchange Regge contributions, a further step might be to use virtual pions as targets to study inelastic $\pi^{\pm}p_1$ reactions with the polarized beam. This could give valuable phase shift information in the resonance region on channels like

These reactions require forward π^0 and/or neutron detection for the beam fragmentation products. From one pion production we can already check that off-shell elastic phases are the same as in $\pi^{\pm}p$ formation reactions,

specifically from EMS experiments on

These elastic channels could calibrate a variety of inelastic virtual pion target experiments.

11. Formalism for $NN \rightarrow NN\pi$

In this section we record relations that are useful in analysis of polarized beam data. We include examples of applications. These equations are presently used by computer programs that predict observables numerically for given model amplitudes, and which also calculate formal representations of each observable (spherical harmonic moment) as a sum of bilinear amplitude contributions. We find that the computer is valuable not only for numerical predictions, but also for purely formal algebraic manipulations, simply because we have to keep track of so many amplitudes, observables and Clebsch-Gordan coefficients. Given the complexity of the problem it seems unlikely that foreseeable experiments will be able to work back from observables to amplitudes in a model independent way. On the other hand the plethora of observables should suffice to refute the simplest models or indicate how to correct them.

This section contains three sub-headings, dealing with (1) conventions and differential cross sections, (2) representation of angular distribution moments, including spin correlations, and their relation to helicity amplitudes, and (3) isospin decomposition. Note that pp elastic scattering can be treated as a ridiculously simple example of our more general formulae (i.e.,

production of a $\frac{1}{2}^+ N^*$, while double pion production is too complicated for consideration here.

II-A Conventions

The process considered is illustrated in Fig. 1. We choose a convenient invariant normalization such that the forward differential cross section (beam fragmentation only) integrated over N^* decay angles, is written

$$2.58 P_{\text{lab}}^2 m_N^2 \frac{d^2\sigma}{d\Omega dm} = \frac{1}{64\pi} \cdot \frac{1}{4} \sum_{\lambda, \lambda', \beta, J, L, M, \mu} |M_{\lambda'\lambda}^{LJM\beta} \cdot g_{J\mu}^L|^2 \cdot \frac{2}{2J+1} \quad (1)$$

σ is in mb., all other units are GeV, and

$M_{\lambda'\lambda}^{LJM\beta}$ = production amplitude for N^* with

J = spin of N^*

L = orbital momentum of N^*

M = helicity of N^*

$\beta = \pm 1/2$ = beam helicity

$\lambda = \pm 1/2$ = target helicity

$\lambda' = \pm 1/2$ = recoil nucleon helicity

$g_{J\mu}^L = N^*$ decay amplitude with

$\mu = \pm 1/2$ = helicity of decay nucleon

Parity conservation gives

$$M_{-\lambda'-\lambda}^{LJM-\beta} = (-1)^{1/2+J+L+\beta+M+\lambda+\lambda'} M_{\lambda'\lambda}^{LJM\beta} \quad (2)$$

$$g_{J-1/2}^L = (-1)^{L+J-1/2} g_{J1/2}^L \quad (3)$$

It is convenient to write the observables in terms of natural and unnatural parity exchange amplitudes (asymptotically) and these are:

$$N_{\lambda'\lambda}^{LJM} = \frac{1}{2} \left[M_{\lambda'\lambda}^{LJM1/2} + (-1)^{L+J+M} M_{\lambda'\lambda}^{LJM-1/2} \right] \quad (4a)$$

$$U_{\lambda'\lambda}^{LJM} = \frac{1}{2} \left[M_{\lambda'\lambda}^{LJM1/2} - (-1)^{L+J+M} M_{\lambda'\lambda}^{LJM-1/2} \right] \quad (4b)$$

Thus we can drop the index β (beam helicity); instead of keeping track of $\beta = \pm 1/2$ we now keep track of N and U amplitudes. Parity conservation in the production amplitudes (Eq. 2) now implies

$$N_{\frac{1}{2}\frac{1}{2}}^{LJM} = N_{-\frac{1}{2}-\frac{1}{2}}^{LJM} \quad (5a)$$

$$U_{\frac{1}{2}\frac{1}{2}}^{LJM} = -U_{-\frac{1}{2}-\frac{1}{2}}^{LJM} \quad (5b)$$

$$N_{\frac{1}{2}-\frac{1}{2}}^{LJM} = -N_{-\frac{1}{2}\frac{1}{2}}^{LJM} \quad (5c)$$

$$U_{\frac{1}{2}-\frac{1}{2}}^{LJM} = U_{-\frac{1}{2}\frac{1}{2}}^{LJM} \quad (5d)$$

We can now rewrite the invariant cross section, Eq. 1, as follows

$$2.58 P_{\text{lab}}^2 m_N^2 \frac{d^2\sigma}{d\Omega dm} = \frac{1}{64\pi} \sum_{\lambda'=\pm\frac{1}{2}, J, L, M, \mu} \left[|N_{\lambda'\frac{1}{2}}^{LJM}|^2 + |U_{\lambda'\frac{1}{2}}^{LJM}|^2 \right] \cdot |g_{J\mu}^L|^2 \cdot \frac{2}{2J+1} \quad (6)$$

Note that $g_{J\mu}^L$, the decay amplitude, can be taken to be ± 1 , and Watson factors like $\sin \delta_J^L e^{i\delta_J^L}$ can be inserted into the production amplitudes. Thus the sum over μ in Eq. 6 can be replaced by an over all factor of 2. However, for computing polarization observables involving the decay nucleon, we have to distinguish $g_{J\frac{1}{2}}^L$ from $g_{J-\frac{1}{2}}^L$ via Eq. 3.

Reference frames: We use Jackson's phase conventions,⁽¹⁾ omitting an extra rotation employed in the Jacob and Wick formalism. This affects only the coordinate frame that describes the decay nucleon polarization (if we measure the final state nucleon spin). For the particles involved in

the production reaction ($3 N^*$'s and $1 N^*$), the y axis = production normal and the z axis is defined in the production plane for each particle separately. In the s channel, z is along the C. M. momentum direction for each particle. In the t channel z for an outgoing particle is defined as the direction of the incoming particle i , the outgoing particle rest frame; the same z axis is used to quantize the initial particle helicity in its rest frame. It is important

note that even though the beam (or target) polarization may be transverse in the s channel frame (along $x = y \times z$), it will nevertheless have a longitudinal component in the t channel frame (along z). For the decay nucleon, the z axis is along the nucleon direction in the N^* rest frame and y is along the normal to the decay plane (same for both s and t channels).

Examples: It may be useful to record our empirical estimates of some amplitudes. For π^+ exchange producing a pure isospin state (as in $pp \rightarrow \Delta^{++}n$) a first order description in the t channel is:

$$N_{\lambda_1 \lambda_2}^{LJM} = 0 \text{ except for absorptive cuts}$$

$$U_{\lambda_1 \lambda_2}^{LJM} \approx \delta_{M \frac{1}{2} \lambda_1 \frac{1}{2}} 293 \frac{\sqrt{t} F(t)}{t + \mu^2} \frac{m_{N\pi}}{\sqrt{q}} \frac{2J+1}{2} \left(\frac{\eta_J^L e^{2i\delta_J^L}}{2i} - 1 \right) \quad (7)$$

$$\delta_{J \frac{1}{2}}^L = 1$$

$$\text{The factor } 293 = \sqrt{\frac{64\pi}{2}} \frac{G^2 \pi N N}{4\pi}$$

$$F(t) \sim e^{-3(t + \mu^2)} \text{ accounts for absorption}$$

$$m_{N\pi} = N^* \text{ invariant mass}$$

$$q = \pi \text{ momentum in } N^* \text{ decay rest frame;}$$

The off-shell πp scattering amplitude is assumed to be the same as the on-shell amplitude, that is δ_J^L is independent of t . For exchanges other than the

pion, we might retain only resonant N^* states and make the replacement

$$\frac{\eta_J^L e^{2i\delta_J^L}}{2i} - 1 \rightarrow \sin \delta_J^L e^{i\delta_J^L} f_J^L \quad (8)$$

where f_J^L is an appropriate branching factor and δ_J^L are phases chosen to give Breit-Wigner behaviour with background removed.

The differential cross sections integrated over mass for the π exchange contribution from Eq. 7 can then be written

$$2.58 P_{\text{lab}}^2 m_N^2 \frac{d\sigma}{dt} \approx \sum_{J,L} 29.2 \frac{t |F(t)|^2}{(t + \mu^2)^2} \cdot \left[\int dm \frac{m^2}{q} \sin^2 \delta_J^L \cdot \frac{2J+1}{2} \cdot R^2 \right] \quad (9)$$

where R^2 denotes the branching ratio squared into πN .

For specific resonances the integral over mass in brackets is:

$$\left(\int dm \frac{m^2}{q} \sin^2 \delta_J^L \cdot \frac{2J+1}{2} \cdot R^2 \right) \approx 2.5 \text{ GeV}^2 (\Delta^{++} 1236) \quad (10)$$

$$.6 \text{ GeV}^2 (N^*_{1520})$$

$$.5 \text{ GeV}^2 (N^*_{1688} - D_{15})$$

$$1.2 \text{ GeV}^2 (N^*_{1688} - F_{15})$$

Appropriate isospin factors have to be added to Eq. 10 for the specific $N\pi$ charge states in the reaction, and these are given in subsection 11-C. A

very rough approximation is then

$$\left(\frac{P_{\text{lab}}}{6} \right)^2 \frac{d\sigma}{dt} \approx 4.3 \cdot I(J, L) e^{-10t} \text{ mb/GeV}^2 \quad (11)$$

where $I(J, L)$ is the integral over N^* mass defined by Eq. 10.

Other exchanges give different amplitude structures that are not so easily predicted. By analogy with elastic scattering we expect Pomeron exchange to contribute mainly to $N_{\frac{1}{2} \frac{1}{2}}^{LJ \frac{1}{2}}$ in the s channel (natural parity-helicity

conserving). Morrison's rule also prescribes L and J such that $J^P = \frac{1}{2}^+, \frac{3}{2}^-$, $\frac{5}{2}^+$, etc. (same naturality as the nucleon). Note that Deck amplitudes are also natural parity but conserve helicity in the t -channel rather than the s -channel.

For Δ^{++} production ρ and A_2 exchange can be predicted from the quark model. In the t -channel, in the absence of absorption, all amplitudes vanish except

$$N_{\lambda' \frac{1}{2}}^{\frac{LJ}{2}} = \sqrt{3} N_{\lambda' \frac{1}{2}}^{\frac{LJ}{2}}. \quad (12)$$

For B exchange we have

$$U_{++}^{\frac{LJ}{2}} = -\sqrt{3} U_{++}^{\frac{LJ}{2}}, \quad (13)$$

but B exchange also contributes to $U_{++}^{\frac{LJ}{2}}$.

II-B Spin Correlation Observables

We have written the differential cross section in terms of amplitudes that describe production (M, N , and U) of the N^* , multiplied by decay amplitudes (g) that define the transitions to the final πN system. The complete amplitude for definite nucleon helicities in initial and final states requires a sum over the intermediate N^* states (L, J, M), which are not directly observed. Properly normalized, this amplitude is

$$\langle \mu' \lambda' | A | \beta \lambda \rangle = \sum_{JML} M_{\lambda' \lambda}^{LJM\beta} g_{J\mu}^L \frac{D_{M\mu}^{*J}(\theta, \varphi)}{\sqrt{2\pi}} \quad (14)$$

where

$$D_{M\mu}^{*J}(\theta, \varphi) = e^{iM\varphi} d_{M\mu}^J(\cos \theta); \theta, \varphi \text{ are } N^* \text{ decay angles.}$$

This can be rewritten in the matrix form

$$\langle \mu' \lambda' | A | \beta \lambda \rangle = \sum_{LJM} u^\dagger(\lambda') \cdot \left[N_{++}^{LJM} \cdot \underline{\underline{1}} + N_{+-}^{LJM} \cdot \underline{\underline{i\sigma_y}} \right] \cdot u(\lambda) \cdot u^\dagger(\mu) \cdot \underline{\underline{M}}_{++}^{LJM} \cdot u(\beta) + u^\dagger(\lambda') \cdot \left[U_{++}^{LJM} \cdot \underline{\underline{\sigma_z}} + U_{+-}^{LJM} \cdot \underline{\underline{\sigma_x}} \right] \cdot u(\lambda) \cdot u^\dagger(\mu) \cdot \underline{\underline{M}}_{+-}^{LJM} \cdot u(\beta) \quad (15)$$

where the quantities doubly underlined are 2×2 matrices, namely

$\sigma_x, \sigma_y, \sigma_z$ = Pauli Matrices

$$M_{\xi}^{LJM} = \frac{1}{\sqrt{2\pi}} \begin{bmatrix} D_{M\frac{1}{2}}^{*J} & -\xi \xi_p D_{M-\frac{1}{2}}^J \\ -\xi_p D_{M-\frac{1}{2}}^{*J} & -\xi D_{M\frac{1}{2}}^J \end{bmatrix}$$

$\xi = \pm$ denotes exchanged naturality as implied by Eq. 15

$\xi_p = (-1)^{L+J+\frac{1}{2}}$ denotes naturality of produced N^* system

$u(a)$ = complex, 2-component spinor that describes a

state with helicity a , specifically

$$u(\frac{1}{2}) = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad u(-\frac{1}{2}) = \begin{pmatrix} 0 \\ 1 \end{pmatrix}.$$

We have set $\frac{L}{g_{J\frac{1}{2}}} = 1$ in Eq. 15 and have employed Eqs. 3-5 to obtain

Eq. 15. Since we measure polarization vectors rather than helicities, it is

necessary to write the spinors in terms of Cartesian polarization vectors.

The nucleon density matrix expresses the spinor amplitudes in terms of polarization as follows

$$\rho = \begin{bmatrix} u(\frac{1}{2}) u^\dagger(\frac{1}{2}) & u(\frac{1}{2}) u^\dagger(-\frac{1}{2}) \\ u(-\frac{1}{2}) u^\dagger(\frac{1}{2}) & u(-\frac{1}{2}) u^\dagger(-\frac{1}{2}) \end{bmatrix} = \frac{1}{2} \cdot 1 + \frac{1}{2} \vec{P} \cdot \vec{\sigma} = \frac{1}{2} \begin{bmatrix} 1+P_z & P_x - iP_y \\ P_x + iP_y & 1-P_z \end{bmatrix}. \quad (16)$$

Now we can square the right-hand side of Eq. 15, replacing uu^* terms with appropriate polarization components from Eq. 16, to define the cross section $|\langle \mu^i \lambda^i | A | \beta \lambda \rangle|^2$. More generally we can express the joint density matrix for the final state nucleons, by squaring Eq. 15, as follows:

$$2.58 P_L^2 m_n^2 \frac{d^4 \sigma}{d\Omega d\Omega' d\Omega'' d\Omega'''} \cdot \left(p_{\text{recoil}} \right)_{ab} \left(p_{\text{decay}} \right)_{cd} = \frac{1}{64\pi} \sum_{\substack{LJM \\ L'J'M' \\ \xi, \xi'}} \left(T_{\xi}^{LJM} p_{\text{target}} T_{\xi'}^{L'J'M'^*} \right)_{ab} \cdot \left(M_{\xi}^{LJM} p_{\text{beam}} M_{\xi'}^{L'J'M'^*} \right)_{cd} \quad (17)$$

where

$p_{\text{beam}}, p_{\text{target}}, p_{\text{recoil}}, p_{\text{decay}}$ are density matrices for the respective nucleons

$$\begin{aligned} T_+^{LJM} &= N_{++}^{LJM} \cdot 1 + N_{+-}^{LJM} \cdot i\sigma_y \\ T_-^{LJM} &= U_{++}^{LJM} \sigma_z + U_{+-}^{LJM} \sigma_x \end{aligned}$$

As indicated, the components of p_{recoil} ("ab") are given by the first matrix on the RHS of Eq. 17, and the components of p_{decay} ("cd") by the second. Thus we can define any observable for the final state baryons as follows:

$$2.58 P_L^2 m_n^2 \frac{d^4 \sigma}{d\Omega d\Omega' d\Omega'' d\Omega'''} p_a^{\text{recoil}} p_b^{\text{decay}} = \frac{1}{256\pi} \sum_{\substack{LJM \\ L'J'M' \\ \xi \xi'}} \text{Trace} \left[\sigma_a \cdot T_{\xi}^{LJM} \cdot (1 + \sigma \cdot \vec{p}_{\text{target}}) \cdot T_{\xi'}^{L'J'M'^*} \cdot \text{Trace} \left[\sigma_b \cdot M_{\xi}^{LJM} \cdot (1 + \sigma \cdot p_{\text{beam}}) \cdot M_{\xi'}^{L'J'M'^*} \right] \right] \quad (18)$$

where

$$\begin{aligned} P_a &= P_x, P_y, P_z \text{ or } 1 \\ \sigma_a &= \sigma_x, \sigma_y, \sigma_z \text{ or } 1 \end{aligned}$$

Thus, if p_{recoil} or p_{target} is unobserved, we set the respective σ_a or $\sigma_b = 1$ on the RHS of 18; any observed component of p_{recoil} or p_{target} is gotten by substituting the appropriate component of σ in the traces in Eq. 18.

The reader can derive any desired correlation from Eq. 18, from 0-spin to 4-spin measurements. We list for convenience in Table I 0, 1, and 2-spin correlations involving beam, target, and decay nucleons. The decay polarization is of interest for processes $N^* \rightarrow \pi K$, and of course the formalism applies to these reactions as well as to $NN\pi$ final states. We now must explain the nomenclature of Table I. Expanding Eq. 18, we see that the cross section and decay polarization have pieces proportional to linear and bilinear combinations of beam and target polarizations, schematically

$$\sigma, \sigma \cdot p_i^{\text{decay}} \propto 1 + p_j^{\text{target}} + p_k^{\text{beam}} + p_l^{\text{target}} \cdot p_m^{\text{beam}} \quad (19)$$

and we can isolate the dependence of the reaction rate on any combination of polarization components. The entries in Table I are defined by the equation

$$\langle 2.58 P_L^2 m_n^2 \frac{d^4 \sigma}{d\Omega d\Omega' d\Omega'' d\Omega'''} \cdot Q \rangle = \frac{1}{64\pi} \sum_{LJM} F_Q(LJM, L'J'M') \frac{f_{QL'J'M'}^{LJM}}{2\pi} (0, \omega) \quad (20)$$

where

$$F_Q(LJM, L'J'M') = \text{bilinear combinations of amplitudes}$$

$$f_{QL'J'M'}^{LJM} = \text{decay distribution function for the } N^*.$$

$$Q = 1, P_i^{\text{beam}}, P_j^{\text{targ}}, P_K^{\text{decay}}, P_L^{\text{beam}}, P_M^{\text{targ}} \dots \text{etc.}$$

For example, the RHS of Eq. 20 gives: the cross section ($Q = 1$); the dependence of the cross section on $P_j^{\text{targ}}, P_K^{\text{beam}}, P_j^{\text{targ}}, P_K^{\text{beam}}$ (when $Q = P_j^{\text{targ}}, P_K^{\text{beam}}, P_j^{\text{targ}}, P_K^{\text{beam}}$); the dependence of the cross section times decay polarization P_j^{decay} on P_K^{targ} ($Q = P_j^{\text{decay}}, P_K^{\text{targ}}$), and so on.

We hasten to point out that the decay functions $f_{Q, LJM}^{LJM}$ are not linearly independent for all combinations of $(LJM, L'J'M')$ indices. Therefore, in practice, a given Q correlation measures a linear combination of $F_Q(LJM, L'J'M')$ (a sum over $LJM, L'J'M'$). To unravel these combinations we would need different Q measurements which produce formally the same amplitude combinations F_Q . Some of the F_Q entries in Table I are indeed formally the same as previous entries, and these are referred back to the previous Q . Thus, although different Q 's may measure the same combination $F_Q(LJM, L'J'M')$, the measurements are not in fact redundant.

The $f_{Q, LJM}^{LJM}(\theta, \varphi)$, can be written as sums of spherical harmonics using the addition theorem for rotation functions. We can write

$$f_{Q, LJM}^{LJM}(\Omega) = \sum_{l, m} a_{Q, LJM}^{LJM}(l, m) Y_l^m(\Omega) \quad (21)$$

and we can write the observables (averaged over decay angles) as

$$\langle 2.58 P_L^2 m_N^2 \frac{d^2\sigma}{d\Omega d\Omega'} \cdot Q \cdot Y_l^m \rangle = \frac{1}{64\pi} \sum_{LJM, L'J'M'} F_Q(LJM, L'J'M') a_{Q, LJM}^{LJM}(l, m) \quad (22)$$

The coefficients "a" are calculated by computer; " Y_l^m " should be $\text{Im} Y_l^m$ when Q contains an odd number of P_x or P_z components, and to $\text{Re} Y_l^m$ for an even number.

Separation of Natural and Unnatural Parity Exchange.

If the target and recoil polarization are measured (not included in Table I), the natural and unnatural parity cross sections are separated by the depolarization measurement. We can see directly from Eq. 15 that natural parity conserves the target nucleon spin along the production normal, while unnatural parity flips the spin. Thus, the dependence of P_y^{recoil} on P_y^{targ} is given by

$$\langle 2.58 P_L^2 m_N^2 \frac{d^2\sigma}{d\Omega d\Omega'} D_{yy} \rangle = \frac{1}{64\pi} \text{Re} \sum_{\lambda'} N_{\lambda' \frac{1}{2}}^{LJM} N_{\lambda' \frac{1}{2}}^{*L'J'M'} - U_{\lambda' \frac{1}{2}}^{LJM} U_{\lambda' \frac{1}{2}}^{*L'J'M'} \cdot \frac{\text{Re} Z_{MM'}^{JJ'}(t)}{2\pi} \quad (23)$$

where $D_{yy} = P_y^{\text{recoil target}} / P_y$ in the notation of Table I. D_{yy} is measured schematically by the ratio

$$D_{yy} = \frac{(1 \rightarrow 1) + (1 \rightarrow 1) - (1 \rightarrow 1) - (1 \rightarrow 1)}{(1 \rightarrow 1) + (1 \rightarrow 1) + (1 \rightarrow 1) + (1 \rightarrow 1)} \quad (24)$$

From Table I, other measurements that separate natural from unnatural exchange are:

(1) Comparison of P_z^{beam} and P_x^{beam} or P_y^{beam} separates

$\text{Im} \sum_{\lambda'} N_{\lambda' \frac{1}{2}}^{LJM} N_{\lambda' \frac{1}{2}}^{*L'J'M'}$ from $\text{Im} \sum_{\lambda'} U_{\lambda' \frac{1}{2}}^{LJM} U_{\lambda' \frac{1}{2}}^{*L'J'M'}$ for terms with $\text{Im} Z_{MM'}^{JJ'} \neq 0$ (specifically $M \neq M'$). With $M = 3/2$, $M' = -1/2$ this comparison provides a test of the quark model for charge exchange reactions, from Eqs. 12 and 13; it tells whether beam polarization effects (P_y^{beam} correlations) are due to natural or unnatural exchange.

(2) The decay nucleon polarization correlations $P_{x,y,z}^{\text{beam}} \cdot P_{x,y,z}^{\text{decay}}$, together with the cross section, allow the separation $\text{Re} \sum_{\lambda'} N_{\lambda' \frac{1}{2}}^{LJM} N_{\lambda' \frac{1}{2}}^{*L'J'M'}$ from $\text{Re} \sum_{\lambda'} U_{\lambda' \frac{1}{2}}^{LJM} U_{\lambda' \frac{1}{2}}^{*L'J'M'}$.

Note that this is the same separation achieved in a target-recoil depolarization measurement. However, many more Q's are measured in this case (10 in all), which allows a more thorough separation of the (LJM) contributions as discussed above.

In principle these measurements could be done by analyzing the decay nucleon in polarized beam interactions with a carbon block. The analysing power is about 5% at 6 GeV/c with an optimal polarimeter. The same apparatus could of course be used to measure D_{nn} at the NN vertex by measuring reactions where the unpolarized target fragments into an N^* and the polarized beam becomes the "target" nucleon. It is clear that such measurements are unlikely to yield more than a qualitative estimate of natural and unnatural parity contributions. In certain cases, for example in the quark model test proposed above, the cross section or polarization could a priori be due to natural or unnatural exchange, and even a rough separation would be very illuminating. For diffractive processes (π exchange explicitly removed), such a separation would be useful to verify crudely that natural parity dominates (to see if there are any surprises).

We can integrate the observables in Table I over N^* decay angles. This integration eliminates interference between states with different J (and excluding decay polarizations, states with different L); realistically experiments using a polarized target may be limited to integrated asymmetries simply because of statistical precision, although dependence on mass and t may be measurable. We can express the result as follows:

$$\langle 2.58 P_{lab}^2 m_N^2 \frac{d^2\sigma}{d\Omega dm} \cdot Q \rangle = \frac{1}{64\pi} \sum_{J,M} \frac{4}{2J+1} \cdot F_Q(J,M) \quad (25)$$

For $Z = 1$, the differential cross section, Eq. 25, is the same as Eq. 6 except that we have summed over decay helicity μ . Table II gives the amplitude combinations F_Q for integrated spin observables Q associated with polarized beam and/or target.

To illustrate these integrated correlations, consider the effect of a single channel,

$$pp \rightarrow p\pi^+n \quad (26)$$

on the spin correlation in the total cross section, $\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}$. According to Table II we should sum over transverse polarizations, and obtain

$$\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow} \propto \frac{d^2\sigma}{d\Omega dm} \cdot (P_x^B P_x^T + P_y^B P_y^T) \quad (27)$$

At low energies, reaction 26 is dominated by π exchange and the main amplitude is $U_{+-}^{LJ\frac{1}{2}}$ in the s-channel (we work in the s-channel because the beam and target polarizations can be chosen experimentally to be transverse in the s-channel). Amplitudes like U_{++}^{LJM} are probably small (A_1 exchange). Natural parity exchange, N_{++}^{LJM} , may be present (ρ or A_2 exchange at the p-n vertex) but we expect ρ and A_2 to have mainly flip coupling, e.g., N_{+-}^{LJM} . Thus we expect a small contribution to the spin correlation from this channel, namely

$$\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow} = \sum_{J,L} \left[\underbrace{\text{Re}(N_{++}^{LJ-\frac{1}{2}} U_{+-}^{*LJ\frac{1}{2}})}_{(\Lambda_2 + \rho) \cdot \pi} - \underbrace{\text{Im}(U_{+-}^{LJ\frac{1}{2}} U_{++}^{*LJ-\frac{1}{2}})}_{\pi \cdot \Lambda_1} \right] (-1)^{L+J-\frac{1}{2}} \quad (28)$$

Note that π - A_1 interference can be estimated from a polarized target measurement alone (using t and s dependence to exclude natural parity exchange polarization effects).

Another way of estimating the contributions to Eq. 28 is to use the Deck model to describe effectively the ρ exchange contribution (A_2 exchange vanishes in the Deck amplitude). Figure 3 shows two decompositions into Deck (natural parity) plus π -exchange; we can label the process as either Δ^{++} or N^{*+} production, and the natural parity contribution (from virtual πN scattering) is Pomeron for N^{*+} and ρ for Δ^{++} . The two descriptions are equivalent if we put in physical πN scattering amplitudes, and the nonflip natural parity amplitude will be enhanced when the relevant πN subenergy is small.

There are only two double spin correlation from Table II that we expect to be leading order in the canonical exchanges at high energies, namely,

$$\begin{pmatrix} P_x^B & P_z^T \\ P_z^B & P_z^T \end{pmatrix} \propto \sum_{J,L} \text{Re} N_{+-}^{LJ-\frac{1}{2}} U_{+-}^{*LJ\frac{1}{2}} \cdot \quad (29)$$

$$\frac{1}{(A_2 + \rho) + \pi}$$

Here the natural parity contribution is helicity flip at both nucleon and N^* vertices, consistent with quark model prejudices (Eq. 12).

C. Isospin Exchange Contributions

By comparing different charge states we can in principle separate definite isospin exchange contributions in the t -channel. Table III gives a decomposition of the amplitudes for selected (measurable) reactions in isospin space; the amplitudes are specified by the isospin exchange and by the isospin of the N^* state produced. We label the isospin amplitudes as follows:

$\Delta = I = 1$ exchange giving $I = 3/2$ $N\pi$ systems,

$N_1 = I = 1$ exchange giving $I = 1/2$ $N\pi$ systems,

$N_0 = I = 0$ exchange giving $I = 1/2$ $N\pi$ systems.

The normalization is such that for π exchange, the amplitudes N_1 and Δ are given by Eq. 7, with phase shifts $I = 1/2$ (N_1) and $I = 3/2$ (Δ). Any spin observable in Table I (with fixed helicity indices) is then a sum over six bilinear combinations of isospin amplitudes, which can be separated in principle by measuring six independent reactions, as listed in Table III. In practice, assuming π exchange dominance one can presumably estimate Δ^2 , N_1^2 and $\text{Re} N_1^* \Delta$ from the two charge exchange reactions 1 and 2. Then by measuring reactions 5 and 6 ($N^* \rightarrow \pi\pi^+$ channels) one can extract N_0^2 to study diffraction. Thus beam fragmentation studies of reactions 1 and 2 could provide sufficient information on $I = i$ exchange background to do spin parity analysis of diffractively produced N^* 's using reactions 5 and 6. ($N\pi^+$ is a better channel for $I = 1/2$ t^+ - $P\pi^0$.)

In order to make sense out of such an isospin decomposition, we must be willing to describe the reactions as $NN \rightarrow N^* N$, where the π is assigned uniquely (on the basis of rapidity, for example) to one of the final state nucleons. In the Deck model of course, N^* 's are not produced and the pion instead comes from the center of a multiperipheral diagram (Fig. 1). What does the Deck model predict for isospin dependence? Using just the π exchange Deck contribution in Fig. 1, we can easily show that the Deck model implies relations between N_1 and Δ , specifically

$$N_1 = -2\Delta \quad (\text{Deck model}) \quad (30)$$

This follows from the observation that $pp \rightarrow (p\pi^0)p$ has no $I = 1$ exchange in the Deck amplitude because $\pi^0 p \rightarrow \pi^0 p$ can have only $I = 0$ exchange. Clearly this cannot apply to genuine resonance production like $\Delta 1236$, $N^* 1520$ or $N^* 1688$; it can only describe the Deck background caused by p exchange in the $\pi N \rightarrow \pi N$ scattering. This constraint also leads to the Berger-Fox test, namely the polarized target observable P_y^T is given by the interference of N_0 with, respectively $-N_1$ for $pp \rightarrow \pi\pi^+p$ and $+N_1$ for $np \rightarrow p\pi^-p$; thus the production polarizations are opposite depending on whether there is a π^+ or a π^- in the final state, because both $I = 3/2$ and $I = 1/2$ $N\pi$ systems are produced together in the Deck amplitude (with $I = 1$ exchange). Of course at high energies $N_0 \gg N_1$ in the Deck amplitude (this can be checked from the cross section ratio $\frac{pp \rightarrow \pi\pi^+p}{pp \rightarrow p\pi^0p} = 2$ for pure N_0), and polarization effects would then be the only sensitive checks on the Deck relation, Eq. 30.

Reference

1. J. D. Jackson, "Particle and Polarization Angular Distributions", High Energy Physics, Les Houches, 327 (1965).

Figures

1. Graphs depicting (a) beam fragmentation, (b) target fragmentation, (c) Regge exchange contributions, Pomeron contributions, and Deck contributions.
2. Cross section for diffractive productions of $J^P = \frac{1}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+ \dots$ states; the production amplitude is a constant multiplied by the respective πN phase shift amplitudes.
3. Two pairs of graphs involving π exchange plus Deck mechanism that can give beam-target spin correlations in $pp \rightarrow p\pi^+n$.

TABLE I

Helicity Decomposition

Spin Observable	Amplitude Combination	Angular Distribution Function
Q	$F_Q(LJM, L'J'M')$	$f_{Q L'J'M'}^{LJM}(\Omega)$
1	$\text{Re} \sum_{\lambda'} \left[N_{\lambda' \frac{1}{2}}^{LJM} N_{\lambda' \frac{1}{2}}^{*L'J'M'} + U_{\lambda' \frac{1}{2}}^{LJM} U_{\lambda' \frac{1}{2}}^{*L'J'M'} \right]$	$\text{Re} Z_{MM'}^{JJ'}$
$P_x^{\text{Beam (B.)}}$	$\text{Im} \sum_{\lambda'} \left[N_{\lambda' \frac{1}{2}}^{LJ-M} N_{\lambda' \frac{1}{2}}^{*L'J'M'} - U_{\lambda' \frac{1}{2}}^{LJ-M} U_{\lambda' \frac{1}{2}}^{*L'J'M'} \right]$	$\text{Im} Z_{MM'}^{JJ'} \cdot (-1)^{J+M+L}$
P_y^{Beam}	$= P_x^{\text{Beam}}$	$\text{Re} Z_{MM'}^{JJ'} \cdot (-1)^{J+M+L+1}$
P_z^{Beam}	$\text{Im} \sum_{\lambda'} \left[N_{\lambda' \frac{1}{2}}^{LJM} N_{\lambda' \frac{1}{2}}^{*L'J'M'} + U_{\lambda' \frac{1}{2}}^{LJM} U_{\lambda' \frac{1}{2}}^{*L'J'M'} \right]$	$-\text{Im} Z_{MM'}^{JJ'}$
$P_x^{\text{Target (T.)}}$	$\text{Im} (N_{++}^{LJM} U_{+-}^{*L'J'M'} + N_{+-}^{LJM} U_{++}^{*L'J'M'})$	$-2 \text{Im} Z_{MM'}^{JJ'}$
P_y^{Target}	$\text{Im} (N_{+-}^{LJM} N_{++}^{*L'J'M'} + U_{+-}^{LJM} U_{++}^{*L'J'M'})$	$-2 \text{Re} Z_{MM'}^{JJ'}$
P_z^{Target}	$\text{Im} (N_{++}^{LJM} U_{++}^{*L'J'M'} - N_{+-}^{LJM} U_{+-}^{*L'J'M'})$	$-2 \text{Im} Z_{MM'}^{JJ'}$
$P_x^B P_x^T$	$\text{Re} \left[N_{++}^{LJM} U_{+-}^{*L'J'M'} + N_{+-}^{LJM} U_{++}^{*L'J'M'} \right]$	$2 \text{Re} Z_{MM'}^{JJ'} (-1)^{L+J+M}$
$P_x^B P_y^T$	$\text{Im} \left[N_{+-}^{LJ-M} N_{++}^{*L'J'M'} - U_{+-}^{LJ-M} U_{++}^{*L'J'M'} \right]$	$2 \text{Im} Z_{MM'}^{JJ'} (-1)^{L+J+M}$

Table I (Cont'd)

Spin Observable	Amplitude Combination	Angular Distribution Function
Q	$F_Q(LJM, L'J'M')$	$f_{Q L'J'M'}^{LJM}(\Omega)$
$P_x^B P_z^T$	$\text{Re} \left[N_{++}^{LJM} U_{++}^{*L'J'M'} - N_{+-}^{LJM} U_{+-}^{*L'J'M'} \right]$	$2 \text{Re} Z_{MM'}^{JJ'} (-1)^{L+J+M}$
$P_y^B P_x^T$	$P_x^B P_x^T$	$2 \text{Im} Z_{MM'}^{JJ'} (-1)^{L+J+M+1}$
$P_y^B P_y^T$	$= P_x^B P_y^T$	$2 \text{Re} Z_{MM'}^{JJ'} (-1)^{L+J+M}$
$P_y^B P_z^T$	$\text{Re} \left[N_{++}^{LJ-M} U_{++}^{*L'J'M'} - N_{+-}^{LJ-M} U_{+-}^{*L'J'M'} \right]$	$2 \text{Im} Z_{MM'}^{JJ'} (-1)^{L+J+M}$
$P_z^B P_x^T$	$= P_x^B P_x^T$	$2 \text{Re} Z_{MM'}^{JJ'}$
$P_z^B P_y^T$	$= P_y^T$	$-2 \text{Im} Z_{MM'}^{JJ'}$
$P_z^B P_z^T$	$= P_x^B P_z^T$	$2 \text{Re} Z_{MM'}^{JJ'}$
$P_x^{\text{Decay Nuc. (D.N.)}}$	$= P_z^B$	$\text{Im} X_{MM'}^{JJ'} (-1)^{L'+J'+\frac{1}{2}}$
$P_y^{\text{D.N.}}$	$= P_z^B$	$\text{Re} Y_{MM'}^{JJ'} (-1)^{L'+J'+\frac{1}{2}}$
$P_z^{\text{D.N.}}$	$= P_z^B$	$-\text{Im} Z_{MM'}^{JJ'}$

27.

Notes on Table I

The functions $f_{JJ'}^{MM'}$ (C) are defined as follows:

$$\begin{aligned} Z_{MM'}^{JJ'} &= e^{i(M-M')\phi} \left[d_{M_2^J M_2^{J'}}^{J J'} + (-1)^{L+L'+J+J'+1} d_{M-\frac{1}{2} M-\frac{1}{2}}^{J J'} \right] \\ \hat{Z}_{MM'}^{JJ'} &= e^{i(M-M')\phi} \left[d_{M_2^J M_2^{J'}}^{J J'} - (-1)^{L+L'+J+J'+1} d_{M-\frac{1}{2} M-\frac{1}{2}}^{J J'} \right] \\ X_{MM'}^{JJ'} &= e^{i(M-M')\phi} \left[d_{M_2^J M_2^{J'}}^{J J'} + (-1)^{L+L'+J+J'+1} d_{M-\frac{1}{2} M-\frac{1}{2}}^{J J'} \right] \\ Y_{MM'}^{JJ'} &= e^{i(M-M')\phi} \left[d_{M_2^J M_2^{J'}}^{J J'} - (-1)^{L+L'+J+J'+1} d_{M-\frac{1}{2} M-\frac{1}{2}}^{J J'} \right] \end{aligned}$$

The argument of the d-functions is $\cos \theta$, the N° decay polar angle. Various relations can be derived between these functions, for example

$$Z_{MM'}^{JJ'} = Z_{MM'}^{J'J'}$$

$$Z_{MM'}^{JJ'} = (-1)^{J+J'+M+M'+L+L'} Z_{-M-M'}^{JJ'}$$

Integrals of these functions over decay angles are:

$$\int d\Omega \operatorname{Re} Z_{MM'}^{JJ'} = \frac{8\pi}{2J+1} \delta_{LL'} \delta_{JJ'} \delta_{MM'} \delta_{MM'}$$

$$\int d\Omega \operatorname{Re} \hat{Z}_{MM'}^{JJ'} = \frac{8\pi}{2J+1} \delta_{LL'+1} \delta_{JJ'} \delta_{MM'} \delta_{MM'}$$

$$\int d\Omega \operatorname{Re} X_{MM'}^{JJ'} = \delta_{LL'} \delta_{JJ'} \delta_{MM'} \frac{4\pi}{2J+1} \int_{-1}^1 d_{M_2^J M_2^{J'}}^{J J'} d_{M-\frac{1}{2} M-\frac{1}{2}}^{J J'} d \cos \theta$$

$$\int d\Omega \operatorname{Re} Y_{MM'}^{JJ'} = \delta_{LL'+1} \delta_{JJ'} \delta_{MM'} \frac{4\pi}{2J+1} \int_{-1}^1 d_{M_2^J M_2^{J'}}^{J J'} d_{M-\frac{1}{2} M-\frac{1}{2}}^{J J'} d \cos \theta$$

$$\int d\Omega \operatorname{Im} Z, \hat{Z}, X, Y = 0$$

Table I (Cont'd)

Spin Observable	Amplitude Combination	Angular Distribution Function
Q	$F_Q(LJM, L'J'M')$	$f_{Q L'J'M'}^{LJM}(\Omega)$
$P_x^B P_x^D N.$	$\operatorname{Re} \sum_{\lambda} \left[N_{\lambda \frac{1}{2}}^{LJ-M} N_{\lambda \frac{1}{2}}^{*L'J'M'} - U_{\lambda \frac{1}{2}}^{LJ-M} U_{\lambda \frac{1}{2}}^{*L'J'M'} \right]$	$\operatorname{Re} X_{MM'}^{JJ'} (-1)^{L+L'+J+J'+M+\frac{1}{2}}$
$P_x^B P_y^D N.$	$= P_x^B P_x^D N.$	$\operatorname{Im} Y_{-MM'}^{JJ'} (-1)^{L+L'+J+J'+M+\frac{1}{2}}$
$P_x^B P_z^D N.$	$= P_x^B P_x^D N.$	$\operatorname{Re} \hat{Z}_{MM'}^{JJ'} (-1)^{J+L+M+1}$
$P_y^B P_x^D N.$	$= P_x^B P_x^D N.$	$\operatorname{Im} X_{MM'}^{JJ'} (-1)^{L+L'+J+J'+M+\frac{1}{2}}$
$P_y^B P_y^D N.$	$= P_x^B P_x^D N.$	$\operatorname{Re} Y_{-MM'}^{JJ'} (-1)^{L+L'+J+J'+M+\frac{1}{2}}$
$P_y^B P_z^D N.$	$= P_x^B P_x^D N.$	$\operatorname{Im} \hat{Z}_{MM'}^{JJ'} (-1)^{J+L+M}$
$P_z^B P_x^D N.$	$\operatorname{Re} \sum_{\lambda} \left[N_{\lambda \frac{1}{2}}^{LJM} N_{\lambda \frac{1}{2}}^{*L'J'M'} + U_{\lambda \frac{1}{2}}^{LJM} U_{\lambda \frac{1}{2}}^{*L'J'M'} \right]$	$\operatorname{Re} X_{MM'}^{JJ'} (-1)^{J'+L'+\frac{1}{2}}$
$P_z^B P_y^D N.$	$= P_z^B P_x^D N.$	$\operatorname{Im} Y_{MM'}^{JJ'} (-1)^{J'+L'+\frac{1}{2}}$
$P_z^B P_z^D N.$	$= P_z^B P_x^D N.$	$\operatorname{Re} \hat{Z}_{MM'}^{JJ'}$

26.

TABLE II

Spin Correlations Integrated Over Decay Angles

Q	$F_Q(LJM)$
I	$\text{Re} \sum_{\lambda} N_{\lambda \frac{1}{2}}^{LJM} ^2 + U_{\lambda \frac{1}{2}}^{LJM} ^2$
P_y^B	$\text{Im} \sum_{\lambda} \left(N_{\lambda \frac{1}{2}}^{LJ-M} N_{\lambda \frac{1}{2}}^{*LJM} - U_{\lambda \frac{1}{2}}^{LJ-M} U_{\lambda \frac{1}{2}}^{*LJM} \right) \cdot (-1)^{L+J+M+1}$
P_y^T	$-2 \text{Im} \left(N_{+-}^{LJM} N_{++}^{*LJM} + U_{+-}^{LJM} U_{++}^{*LJM} \right)$
$P_x^B P_x^T$	$2 \text{Re} \left[N_{++}^{LJ-M} U_{+-}^{*LJM} + N_{+-}^{LJ-M} U_{++}^{*LJM} \right] \cdot (-1)^{L+J+M+1}$
$P_x^B P_z^T$	$2 \text{Re} \left[N_{++}^{LJ-M} U_{++}^{*LJM} - N_{+-}^{LJ-M} U_{+-}^{*LJM} \right] \cdot (-1)^{L+J+M+1}$
$P_y^B P_y^T$	$2 \text{Im} \left[N_{+-}^{LJ-M} N_{++}^{*LJM} - U_{+-}^{LJ-M} U_{++}^{*LJM} \right] \cdot (-1)^{L+J+M}$
$P_z^B P_x^T$	$2 \text{Re} \left[N_{++}^{LJM} U_{+-}^{*LJM} + N_{+-}^{LJM} U_{++}^{*LJM} \right]$
$P_z^B P_z^T$	$2 \text{Re} \left[N_{++}^{LJM} U_{++}^{*LJM} - N_{+-}^{LJM} U_{+-}^{*LJM} \right]$

TABLE III

Isospin Decomposition

Reaction	Isospin Amplitude	Observables
1 $pp \rightarrow (p\pi^+)n$	$-\Delta$	Δ^2
2 $pn \rightarrow (p\pi^-)p$	$\frac{\Delta}{3} + \frac{2}{3} N_1$	$\frac{\Delta^2}{9} + \frac{4}{9} N_1^2 + \frac{4}{9} N_1 \Delta$
3 $pn \rightarrow (n\pi^0)p$	$\frac{\sqrt{2}\Delta}{3} - \frac{\sqrt{2}}{3} N_1$	$\frac{2\Delta^2}{9} + \frac{2}{9} N_1^2 - \frac{4}{9} N_1 \Delta$
4 $pp \rightarrow (p\pi^0)p$	$\frac{\sqrt{2}\Delta}{3} + \frac{\sqrt{2}}{6} N_1 - \frac{\sqrt{2}}{6} N_2$	$\frac{2\Delta^2}{9} + \frac{N_1^2}{18} + \frac{2}{9} N_1 \Delta + \frac{N_0^2}{18} - \frac{2}{9} N_0 \Delta - \frac{N_0^* N_1}{9}$
5 $pn \rightarrow (p\pi^0)p$	$\frac{-\sqrt{2}\Delta}{3} - \frac{\sqrt{2}}{6} N_1 - \frac{\sqrt{2}}{6} N_0$	$\frac{2\Delta^2}{9} + \frac{N_1^2}{18} + \frac{2}{9} N_1 \Delta + \frac{N_0^2}{18} - \frac{2}{9} N_0 \Delta + \frac{N_0^* N_1}{9}$
6 $pp \rightarrow (n\pi^+)p$	$\frac{\Delta}{3} - \frac{N_1}{3} + \frac{N_0}{3}$	$\frac{\Delta^2}{9} + \frac{N_1^2}{9} - \frac{2}{9} N_1 \Delta + \frac{N_0^2}{9} + \frac{2}{9} N_0 \Delta - \frac{2}{9} N_0^* N_1$
7 $pn \rightarrow (n\pi^+)n$	$-\frac{\Delta}{3} + \frac{N_1}{3} + \frac{N_0}{3}$	$\frac{\Delta^2}{9} + \frac{N_1^2}{9} - \frac{2}{9} N_1 \Delta + \frac{N_0^2}{9} - \frac{2}{9} N_0 \Delta + \frac{2}{9} N_0^* N_1$
7' $np \rightarrow (p\pi^-)p$	$\frac{\Delta}{3} - \frac{N_1}{3} - \frac{N_0}{3}$	$\frac{\Delta^2}{9} + \frac{N_1^2}{9} - \frac{2}{9} N_1 \Delta + \frac{N_0^2}{9} - \frac{2}{9} N_0 \Delta + \frac{2}{9} N_0^* N_1$

Figure 3

Inclusive Polarization Measurements at the ZGS

David R. Rust

Introduction

Polarization measurements of 2-body and quasi-2-body reactions have in the past been helpful in constraining phenomenological models of particle interactions. We are now just beginning to understand the dynamics of multi-particle production processes and we expect that polarization measurements will be very useful for removing ambiguities in the description thereof. The Argonne polarized beam provides a unique facility for the study of polarization in multi-particle reactions and we are interested in exploring the possibilities for experiments in this area of research.

There is very little that can be said about polarization inclusive processes without a model. The best known model, the triple Regge model, will be considered in the next section.

Inclusive Polarization Data at Argonne and the Triple Regge Analysis

The energy range of the ZGS overlaps a small part of the range of kinematic variables for which the triple Regge analysis is applicable. Consider for example the reaction $pp \rightarrow pX$. The mass of X must be considerably above the obvious resonances and the ratio $\frac{s}{M_X^2}$ must be much more than 1 for the triple Regge formulas to be applied directly. The lower limit of M_X^2 can be recognized in cross-section data at high energy as the point where $\frac{d\sigma^2}{dtM^2}$ approximately assumes a simple scaling and $1/M_X^2$ behavior. This occurs for $M_X^2 \sim 9(\text{GeV}/c^2)^2$. The largest s available at the ZGS is $s = 25 \text{ GeV}^2$. We thus discover that we are at the very edge of the triple Regge region at Argonne.

The data taken at Argonne can, however, be related to the high mass region by the use of Finite Mass Sum Rules. These rest on general principles. They connect the average behavior of the observations at low mass to the simple behavior at high mass.

The triple Regge analysis needs polarization data to separate the so-called interference terms from the diagonal terms. The diagonal terms are well determined from unpolarized cross-section data.¹⁾ The interference terms (PRP, PRR, $R_1 R_2$, etc.) have not yet been determined because of the lack of polarization data and for this reason the triple Regge analysis remains incomplete at this time.

A good general reference to polarization from a triple Regge viewpoint is found in the paper by Field in the 1974 Summer Study on Physics with Polarized Beams.²⁾ A discussion of Finite Mass Sum Rules is found there.

The experiment which would measure the polarization in the correct kinematic regions of $pp \rightarrow pX$ to provide data for the triple Regge analysis would be done with a polarized beam on a hydrogen target. The asymmetry of the beam associated final state particle (π, K, p) would be observed. This experiment should be done at 12.33 GeV/c. It might be that the polarization oscillates around zero in the region of the resonances and the average might be close to zero. In this case it is important to obtain good statistics over the entire mass range so that the integral over mass, in the Finite Mass Sum Rule, will be significantly different from zero.

In the case of a scattered proton, you can measure its polarization by rescattering it and measuring the asymmetry. This observable and also the depolarization can be expressed as a Finite Mass Sum Rule. Then the difference in natural and unnatural parity exchange cross-sections is measured by D ,²⁾ and the polarization due to natural and unnatural parity exchange can be separated by

$$P_N = P_A + P_C$$

$$P_U = P_A - P_C$$

where P_A is the polarization as measured by the asymmetry in the first scattering and P_C is the polarization measured by the asymmetry in rescattering.

In the case of scattered mesons we can only measure the asymmetry of the scattering. One observes, however, that these reactions are mediated by baryon exchange and that X contains at least two baryons. (The equivalent reaction is e.g. $\pi p \rightarrow \bar{p} X$). There are no dibaryon resonances consequently one doesn't expect to see much structure in the polarization in the low mass region. From a triple Regge point of view, however, these reactions are important for determining couplings with baryon trajectories.

The fact that some $\bar{P}$ and K^- production might be observed in pp collisions is not useful in the simple triple Regge model because there are no valid couplings to be determined. Such processes at high energy and large M_X^2 would suggest more complicated production mechanisms.

After the data are obtained, the polarization and depolarization Finite Mass Sum Rules need to be evaluated with different moments; that is, with $N = 1, 3, 5, \dots$ in the expression 2)

$$I_n^p(s, t, v_0) \equiv \frac{1}{v_0^{n+1}} \int_0^{v_0} v^n P_A(s, t, v) \frac{d\sigma}{dcdv}(s, t, v) dv$$

where $v = M_X^2 - t - M_p^2$.

The different interference couplings depend on n in different ways and this is the reason that more than one coupling can be determined from one set of polarization data. This method depends on the quality of the data for its success. From this we again see how important it is to get data (at several fixed t values) with small errors and closely spaced over the mass range.

There is another type of experiment in which an unpolarized beam is incident on a polarized target and the asymmetry of the scattered particle is measured. This polarization should be zero in the absence of a non-factorizing contribution to the interaction. A measurement at 8 GeV/c^{2,3)} shows essentially no asymmetry for $M_X^2 \geq 5$ (GeV/c²)² but there is an asymmetry at lower M_X^2 . More

measurements would be welcome especially at a higher energy and with better statistic.

There is only one inclusive polarization measurement involving neutrons which recommends itself from an experimental point of view at the present time. This is $pp \rightarrow nX$ ($p \rightarrow n$). A polarized beam would hit a hydrogen target and the asymmetry of a low energy neutron would be observed. It is also of the type where no polarization is expected at high mass in the absence of cuts. In fact it is a partner to the reaction ($p \rightarrow p$) described above in that one cut contribution to the polarization changes sign from one reaction to the other.²⁾

Other Results from Inclusive Polarization Measurements at the ZGS

The measurements which contribute to the Finite Mass Sum Rule integral are interesting in the sense that they will depend on the properties of resonances. Both 6 GeV/c and 12 GeV/c would be useful in observing the behavior of the polarization as the missing mass passes through various resonances. It is important as usual to obtain precise polarization data in as much as the changes in polarization due to the resonances may be small. On the other hand, the polarization is probably more sensitive to the effects of resonances of differing spin-parity than the cross-section. It is in this sense that the measurements of inclusive cross-sections could be exciting independent of the triple Regge analysis.

References

1. R. D. Field and G. C. Fox, Nuclear Physics B80, 367 (1974).
2. R. D. Field, "Polarization Effects in Inclusive Processes" in Proceedings of the Summer Studies on High Energy Physics with Polarized Beams, Argonne National Laboratory, ANL/HEP 75-02.
3. L. Dick et al., Phys. Letters 57B, 93 (1975).

Polarization Effects in Inclusive Processes*

by

R. D. Field

California Institute of Technology, Pasadena, California 91109

ABSTRACT

This paper deals with the phenomenology of polarization and spin effects in inclusive processes. These effects are examined using the triple-Regge formalism valid at large s/M^2 and large M^2 , however the connection between this region and the small M^2 region via finite-mass sum rules (FMSR) and M^2 -duality is emphasized. The two distinct types of polarization effects [ie. type I = $(a \xrightarrow{b} c)$; type II = $(a \xrightarrow{b^\dagger} c)$] are discussed separately and in detail. Examples and predictions are given and existing data examined. Other observables in inclusive processes are also mentioned briefly.

*It was felt by the committee that this review would be helpful for any person using this report. As the report has already been published in the "Summer Study on High Energy Physics with Polarized Beams," ANL/HEP 7502, only the Abstract is reproduced here. Readers interested in inclusive phenomena are urged to consult this reference.