February 1978

REPORT OF THE ANL TECHNICAL ADVISORY PANEL
ON
PHYSICS WITH POLARIZED BEAMS AND TARGETS

PANEL MEMBERS:

A. W. Hendry
R. A. Arndt
D. G. Crabb
E. P. Fischbach
P. W. Johnson
E. A. Peterson
J. B. Roberts
A. A. Seidl
D. P. Sidhu
G. H. Thomas
A. B. Wicklund

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make 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.

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. IT has been reproduced from the best available copy to permit the broadest possible availability.

Mr only

UCC-AUA-USDOE

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

MASTER

Operated under Contract W-31-109-Eng-38 for the
U. S. DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) between the U. S. Department of Energy, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona
Carnegie-Mellon University
Case Western Reserve University
The University of Chicago
University of Cincinnati
Illinois Institute of Technology
University of Illinois
Indiana University
Iowa State University
The University of Iowa

Kansas State University
The University of Kansas
Loyola University
Marquette University
Michigan State University
The University of Michigan
University of Minnesota
University of Missouri
Northwestern University
University of Notre Dame

The Ohio State University
Ohio University
The Pennsylvania State University
Purdue University
Saint Louis University
Southern Illinois University
The University of Texas at Austin
Washington University
Wayne State University
The University of Wisconsin

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, 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. Mention of commercial products, their manufacturers, or their suppliers in this publication does not imply or connote approval or disapproval of the product by Argonne National Laboratory or the U. S. Department of Energy.

REPORT OF THE ANL TECHNICAL ADVISORY PANEL

ON

PHYSICS WITH POLARIZED BEAMS AND TARGETS *

February, 1978

PANEL MEMBERS:

A. W. Hendry	Indiana (Chairman)
R. A. Arndt	VPI and SU
D. G. Crabb	Michigan
E. P. Fischbach	Purdue
P. W. Johnson	IIT
E. A. Peterson	Minnesota
J. B. Roberts	Rice
A. A. Seidl	Michigan
D. P. Sidhu	Brookhaven
G. H. Thomas	Argonne
A. B. Wicklund	Argonne

* Supported in part by the U. S. Department of Energy.

INTRODUCTION

The present Technical Advisory Panel (TAP) was formed at the beginning of the summer of 1977. It follows a similar TAP that was set up about three years ago under the chairmanship of G. Kane. The general purpose of these TAP's is to examine what experiments have already been done at the ZGS, and to give some guidelines for the future direction of the experimental program at the ZGS.

The recommendations of the Kane TAP were presented in the Argonne report:

Physics with Polarized Beams (ANL-HEP-CP-75-73) November 1975
and these have been very useful in guiding the experimental program during the last two or so years. Subsequent to this Kane Report, there have been several other reports and studies concerning the ZGS program. These include, for example,

Long Range Planning Study of the High Energy Program

at ANL

June 1976

(A report of the AUA Special Committee on
High Energy Physics)

Future Operation of the ZGS as a Dedicated Polarized

Proton Facility

June 1976

Report of the 1976 ZGS Review Panel

(Chairman R. L. Walker)

August 1976.

All of these point to the unique features of the ZGS and outline excellent programs.

However, the present time is of particular significance for the ZGS. After a long and fruitful life in which much has been contributed to the development of high energy physics and to our understanding of particle interactions, the ZGS is presently scheduled to end its operation in the not too distant future--October 1979. This means that only a limited number of experiments can be done in the remaining months. It has therefore been the task of this Panel not only to lay out a reasonable program based on interesting physics, but one which could be completed within the time constraint.

Since its inception, the Panel has held two marathon sessions (July 28 and September 8, 1977). There have also been many letters and innumerable telephone calls. Our preliminary recommendations were presented to the Argonne ZGS Advisory Program Committee on October 13.

The present report is in two parts. The first part consists of a brief discussion of recent experimental measurements at the ZGS, their implications, and our recommendations for future experiments. The areas we discuss are as follows

- (A) Elastic proton-proton at small t , 6 GeV/c
- (B) Elastic proton-proton at small t , 12 GeV/c
- (C) Elastic neutron-proton at small t , 6 GeV/c
- (D) Elastic neutron-proton at small t , 12 GeV/c
- (E) Low energy nucleon-nucleon, 1 to 3 GeV/c
- (F) Experiments at large t , large $p_{\perp}$.

This section closes with an overall summary showing the various parts of the nucleon-nucleon picture which we hope will be completed by the

time of the ZGS shutdown. (The Panel did not discuss at length several experiments which are already approved and will be run in the near future. These include for example the Effective Mass Spectrometer experiment to study important exchange mechanisms in $p\uparrow N \rightarrow \Lambda K^+ N$ using a polarized beam, and the Indiana inclusive polarization experiment. Both of these experiments should provide useful information about the detailed dynamics of nucleon-nucleon processes. We did of course spend a considerable amount of time discussing inclusive polarization processes in general, as well as the feasibility of pursuing this line of investigation further.)

The second part of this Report brings together, for convenience of reference, some useful pieces of nucleon-nucleon information frequently used by the practitioners in this field. These include some kinematics and the well-known Table of Halzen and Thomas (Phys. Rev. D10, 344 (1974)) expressing the measurable quantities in terms of the scattering amplitudes. We also provide Tables of conversions between two commonly used momentum transfer variables $-t$ and $p_{\perp}^2$ at 6.0 and 11.75 GeV/c; and between the beam momentum p_{lab} , the beam kinetic energy T and the total center-of-mass energy $\sqrt{s}$ in the possible dibaryon resonance region.

As a further part of the work of the Panel, we have undertaken a compilation of experimental data in the ZGS energy region. This is being done primarily by J. Roberts, E. Peterson and D. Crabb, and will be an expanded update of the summary provided by D. Rust in the Kane 1975 Report. This part will be published separately.

It can be regarded as a great achievement for the experimentalists to have made so many accurate measurements during the last two or so years. The nature of the results has frequently been unexpected. Spin effects seem to be large almost everywhere! They do not go away with increasing angle; they do not always diminish as the beam energy is increased; nor are they washed out by the presence of many inelastic channels. All this of course makes the nucleon-nucleon problem all the more fascinating and worthy of further study.

PART 1

Before we get into specific recommendations, it is useful to see what has been accomplished since the Kane 1975 Report. On the next page, we compare the experimental status before and after 1975. The Table is divided into the four categories of the Kane panel:

1. $NN \rightarrow NN$, small t (35-45%)
2. Quasi-two-body reactions and spectroscopy (25-35%)
3. Inclusive small t (5-10%)
4. New unexplored areas (15-25%)

where the percentages indicate the amount of experimental effort that the Panel recommended should go into the four areas.

We can see at a glance that an enormous amount of experimental data has been obtained during the last two or so years. Experiments have frequently involved extremely difficult measurements. In many places where there was little or no data before, there is now a substantial amount. Experiments just talked about in 1975 as a distant possibility have not only been made to work, but have been completed and have provided us with many useful measurements. The experimental program at the ZGS in the last few years has undoubtedly been extremely fruitful, a great achievement and excellent physics.

What have we learned during these years about particle interactions? The most obvious result of course is that, contrary to general belief, spin interactions are very important. Unfortunately in most theoretical calculations nowadays, spin is usually ignored. This is not because of any basic principle, but mainly because spin is a

SUBDIVISIONS OF KANE REPORT	PRE-1975	POST-1975
<div>1. NN $\rightarrow$ NN, small t (35-45%)</div> <p><u>pp elastic</u> low energies intermediate high</p> <p><u>np elastic</u> <u>$\bar{p}p$ elastic</u> <u>np CEX, $\bar{p}p$ CEX</u></p>	<p>P(1.0 $\rightarrow$ 5.15) P, C_{nn}, D_{nn}(6) P(12) Some P. Very small amount. np CEX P(2 $\rightarrow$ 12)</p>	<p>Flood of data: P, C_{nn}, C_{ll}, C_{ss}, $\Delta\sigma_T$, $\Delta\sigma_L$, (snOs), P(2 $\rightarrow$ 6, 12) --- ---</p>
<div>2. QUASI-2 BODY REACTIONS AND SPECTROSCOPY (25-35%)</div> <p>Diffractive (vac. exch. allowed) Non-diffractive</p>	<p>Initial data on p p $\rightarrow$ N*N, NN*(EMS).</p>	<p>Much more data; partly analyzed.</p>
<div>3. INCLUSIVE SMALL t (5-10%)</div> <p>Meson exchange Baryon exchange</p>	<p>Very small amount.</p>	<p>p p $\rightarrow$ pX p p $\rightarrow$ $\pi^\pm$ and $K^\pm$ X 6, 12 GeV/c</p>
<div>4. NEW UNEXPLORED AREAS (15-25%)</div> <p>Large p inclusive Large t elastic Invariance principles C, P, T</p>	<p>--- Some P(pp). ---</p>	<p>--- P(pp), C_{ln} (esp. at 12 GeV/c). P(np) all angles at 3, 6 GeV/c. Some studies; no violations observed.</p>

complication which people hope will be small and can thus be neglected. The ZGS experiments show that the opposite is frequently the case, and where spin effects were supposed to get small, they usually do not get small! They do not usually become small as the beam energy increases; they do not go away at large momentum transfer; and they are still present in inclusive processes even though many channels are summed over. (There are indications that this is also true even at, for example, Fermilab energies.) Apparently, particle scattering does depend upon spin orientation. Studying spin effects is therefore very important, and since our intuition about spin has often been proven to be very lacking, a careful, methodical study, such as the experimental program at the ZGS, is necessary at any energy. An understanding of particle interactions at anything other than a superficial level demands such a study.

Where do we go from here at the ZGS? There are many interesting experiments that can be done. However, because of the time limitation, not all good experiments that we can think of can be done within the time available. Certainly we do not have the time to start and develop a major new line of experiments. Below, we discuss six areas considered in particular by the present TAP, and make specific recommendations about possible experiments.

(A) Elastic proton-proton scattering at small t , $p_{\text{lab}} = 6 \text{ GeV}/c$.

This is the area which has received the major emphasis during the last two years. The aim of the experiments has been to obtain enough experimental data so that an amplitude analysis can be done for

small- $t \lesssim 1(\text{GeV}/c)^2$ at 6 GeV/c. Why do this? It is of course always useful to obtain amplitudes in a model independent way. However the need for obtaining such model independent amplitudes became even greater as the experiments were being done, since both of the leading contenders among the theories [the strong absorption model of G. Kane and A. Seidl, Rev. Mod. Phys. 48, 309 (1976), and the super-Regge model of R. Field and P. Stevens, Kane 1975 Report] were shown to give wrong predictions. We are therefore at a stage where model builders desperately need some guidance. An amplitude analysis of proton-proton scattering will give us much needed insight into what is happening in this, one of the most basic of all the strong interactions.

What is the present status of these experiments, and how can the amplitudes be extracted? As we shall see, a sufficient number of experiments have been done, though some are still in the process of being analyzed (denoted below by B.A.).

The differential cross-section, given by

$$\sigma = I(00,00) = |N_0|^2 + 2|N_1|^2 + |N_2|^2 + |U_0|^2 + |U_1|^2 \quad [\text{Do\~{n}e}]$$

has been available for some time. This measurement sets the scale for the amplitudes, the other measurable quantities varying between ± 1 . As a first step in the analysis, P. Johnson, R. Miller and G. Thomas [Phys. Rev. D15, 1895 (1977)] have suggested the following strategy. First, assume that N_0 is dominant (and largely imaginary). This is certainly something which all theories have in common. However, this assumption can be checked directly by experiment by measuring

$$\sigma D_{nn} = |N_0|^2 + 2|N_1|^2 + |N_2|^2 - |U_0|^2 - |U_2|^2 \quad [\text{Done}]$$

and

$$\begin{aligned} \sigma D_{zz} &= -I(0t, 0t) \cos \theta_R + I(0t, 0s) \sin \theta_R \\ &= |N_0|^2 - |N_2|^2 + |U_0|^2 - |U_2|^2 \quad [\text{B.A.}] \end{aligned}$$

where θ_R is the lab recoil angle of the target proton. If N_0 dominates, both D_{nn} and D_{zz} (or equivalently $I(0t, 0s)/\sigma$ since θ_R is close to 90° for near forward scattering) should be close to 1. From the D_{nn} measurements available so far, the dominance of N_0 looks like a reasonable assumption, at least for $-t \lesssim 0.5 \text{ (GeV/c)}^2$. Also C_{ts} , which is of the form

$$\sigma C_{ts} = 2 \operatorname{Re}(U_0 + U_2) N_1^* \quad [\text{Done}]$$

is of the order of only a few percent. This is again consistent with N_0 dominance, the other four amplitudes being much smaller.

The next step is to obtain the projections of the other amplitudes on N_0 . We have

$\sigma_P = (0n, 00)$	approximately	$-2 \operatorname{Im} N_0 N_1^*$	[Done]
$\sigma_R = (0s, 0s)$		$-\sigma \cos \theta_R - 2 \operatorname{Re} N_0 N_1^*$	[B.A.]
$(ns, 0s)$		$2 \operatorname{Im} N_0 N_2^*$	[B.A.]
$\sigma_{nn} = (nn, 00)$		$-2 \operatorname{Re} N_0 N_2^*$	[Done]
$(ls, 0n)$		$-2 \operatorname{Im} N_0 U_0^*$	[B.A.]
$\sigma_{ll} = (ll, 00)$		$-2 \operatorname{Re} N_0 U_0^*$	[Done]
$(sn, 0s)$		$2 \operatorname{Im} N_0 U_2^*$	[Done]
$\sigma_{ss} = (ss, 00)$		$2 \operatorname{Re} N_0 U_2^*$	[Done]

We see that data have already been collected for all of these quantities.

In some cases, the analysis is complete; in others, the analysis is still in progress. In addition of course there is the information at $t = 0$ provided by total cross sections and Coulomb interference:

$$\sigma_{\text{tot}} = \frac{4\pi}{k} \operatorname{Im}[N_0(0)] \quad [\text{Done}]$$

$$\Delta\sigma_T = -\frac{8\pi}{k} \operatorname{Im}[U_2(0)] \quad [\text{Done}]$$

$$\Delta\sigma_L = \frac{8\pi}{k} \operatorname{Im}[U_0(0)] \quad [\text{Done}]$$

$$\text{Coulomb interference } \operatorname{Re} N_0(0)/\operatorname{Im} N_0(0) \quad [\text{Done}].$$

Clearly the study of proton-proton elastic scattering for small t at 6 GeV/c is in reasonably good shape. Hopefully it will not be too long before the experimentalists will yield their data in final

form so that a full-scale amplitude analysis can be carried out. The results are expected to be very interesting. Does anything else need to be done? At the moment, there seems to be nothing of high priority. If all goes according to plan, we should know before long the five amplitudes (up to an overall t -dependent phase) for proton-proton elastic scattering at 6 GeV/c in the momentum transfer range $0.1 \lesssim -t \lesssim 0.7 \text{ (GeV/c)}^2$.

Other measurements in this region are frosting on the cake. However, should there be time, we mention two possibilities.

- (i) $I(\pi n, 0s)$. This quantity, which directly provides some information about the real part of the unnatural parity π -like exchange, was the first of the 3-spin measurements to be made at the ZGS. Its errors ($\pm 20\%$) are much larger than one would like. It may be necessary to re-measure this quantity if the large errors have a serious effect on the determination of the amplitudes in the amplitude analysis.
- (ii) $C_{\pi\pi}, C_{nn}, C_{ss}$ at very small t . Apparently it is possible, with some effort, to measure these quantities at values of $-t \lesssim 0.1 \text{ (GeV/c)}^2$, below the presently measured region. (At $t = 0$, $C_{nn} = C_{ss}$ so that it would not be necessary to measure both C_{nn} and C_{ss} .) These measurements would be useful in determining the absolute phases of

the smaller unnatural parity amplitudes at very small t . For example,

$$\sigma_{\ell\ell} \sim -2\text{Re}(N_0 U_0^*) = -2(\text{Re } N_0)(\text{Re } U_0) - 2(\text{Im } N_0)(\text{Im } U_0)$$

$$\sigma_{nn} \sim 2\text{Re}(N_0 U_2^*) = 2(\text{Re } N_0)(\text{Re } U_2) + 2(\text{Im } N_0)(\text{Im } U_2).$$

All the imaginary parts are known from total cross-section measurements, and $\text{Re } N_0$ is known from Coulomb interference. Hence a measurement of $C_{\ell\ell}$ and C_{nn} at very small $-t$ would essentially yield $\text{Re } U_0$ and $\text{Re } U_2$, thus providing an estimate of the phases of the unnatural parity amplitudes at very small $-t$. Phases are of great importance for any theoretical model. Measurement of the absolute phase of any amplitude anywhere provides a crucial test for any theory.

(B) Elastic proton-proton scattering at small t , $p_{\text{lab}} = 12 \text{ GeV}/c$.

Clearly it would be nice to do a full amplitude analysis at $12 \text{ GeV}/c$ in a manner similar to the $6 \text{ GeV}/c$ program that is now almost complete. We would then be able to tell how the individual pp amplitudes are changing with energy. Are they for instance varying in a regular Regge-behaved fashion? It is expected that the natural parity exchange amplitudes will be Regge-behaved (just as they seem to be in pion-nucleon scattering), but in view of the surprises at $6 \text{ GeV}/c$ one is very uncertain about the unnatural parity amplitudes. Again, for

model building and a deeper understanding of pp interactions, it is necessary to have some knowledge of this.

A full amplitude program at 12 GeV/c would however take up too much time. A selection of experiments has to be made, keeping in mind the physics and the experimental equipment readily available. So far, the following quantities have been measured:

$$\frac{d\sigma}{dt}, \quad P \quad \text{and} \quad \sigma_{\text{tot}}. \quad [\text{Done}]$$

The Panel recommends with high priority the measurement of

$$C_{nn}, \quad C_{\ell\ell}, \quad C_{ss}, \quad \Delta\sigma_T \quad \text{and} \quad \Delta\sigma_L.$$

Surprisingly, C_{nn} has already been measured at $-t$ values greater than $0.7(\text{GeV}/c)^2$. There, it shows a great deal of structure, with two distinct oscillations and rising to as much as 30% as it approaches the 90° region. It needs to be measured also at smaller values of $-t \lesssim 0.7(\text{GeV}/c)^2$; it is expected to be as large as 8-10% in this latter region. P and C_{nn} will provide some insight about the energy dependence of the natural parity amplitudes, while the other quantities $C_{\ell\ell}$, C_{ss} , $\Delta\sigma_T$ and $\Delta\sigma_L$ will provide clues about the unnatural parity exchange.

At a lower priority, we place the other quantities (mostly 3-spin measurements) that are necessary for a full amplitude analysis.

(C) Elastic neutron-proton scattering at small t , $p_{\text{lab}} = 6 \text{ GeV/c}$.

Neutron-proton elastic scattering has been another area that has brought a big surprise during the last two or three years. The forward differential cross section is very similar to that for proton-proton scattering. The polarization was expected to be either similar to that for pp (on the basis of a simple geometric picture for the scattering process), or else its mirror symmetric counterpart (on the basis of a simple Regge exchange model with isospin 1 dominating in the t -channel spin flip term). If the measured np polarization had been close to either one of these possibilities, we would have felt that we already knew something about np scattering and not many more measurements would have been necessary. In fact, however, np polarization turns out to be rather complicated. Experiment shows that it is neither simple geometric nor simple Regge. At low energies $p_{\text{lab}} \approx 2 \text{ GeV/c}$, the np polarization is positive and not too different from the pp polarization. But as the energy increases, np polarization at small $-t \lesssim 0.8 (\text{GeV/c})^2$ quickly dies away and starts becoming negative at 12 GeV/c .

These results clearly indicate again that nucleon-nucleon scattering is much more complicated than anyone originally suspected. Not only is spin orientation an important attribute, but apparently so also is isospin exchange. Strong energy dependence is also suspected for at least one amplitude. As a result of these new developments since the Kane 1975 Report, the Panel felt that a careful and extended investigation of np scattering was warranted as a vital part of the remaining ZGS program.

There are two ways of studying these isospin effects, as may be seen from the t-channel isospin decompositions

$$\begin{array}{ll} \text{pp elastic} & \frac{1}{2} (A_0 + A_1) \\ \text{np elastic} & \frac{1}{2} (A_0 - A_1) \\ \text{np CEX} & A_1 . \end{array}$$

The spin structure is the same in all three cases. Thus a feasible program for studying t-channel isospin is to combine the already existing pp data with either np elastic scattering measurements or np CEX measurements. The time limitation precludes doing both. Moreover, whichever one is chosen, only a limited number of experiments is possible in the available time.

np CEX has the advantage that it is pure $I^t = 1$ exchange. However there is no reason to think that any one amplitude will dominate over the others (except where pion exchange dominates in the extreme forward direction). All of its amplitudes are therefore expected to be comparable in size (even though the np CEX amplitudes are small, the spin correlations need not be small). Thus in order to extract any feeling about $I^t = 1$ amplitudes, it will probably be necessary to do a full set of measurements. There is not enough time for this.

np elastic scattering on the other hand is expected to have one dominant amplitude N_0 in the forward scattering region. It is thus possible, by doing a few experiments, to get some idea of what is happening at least for some pieces of the amplitudes. After much discussion, the Panel decided in favor of this route, rather than np CEX.

Experiments already done are

$$\frac{d\sigma}{dt}, \quad P \quad \text{and} \quad \sigma_{\text{tot}}. \quad [\text{Done}]$$

Experiments that should be done, with high priority, are

$$C_{nn}, \quad C_{\ell\ell}, \quad C_{ss}, \quad \Delta\sigma_T \quad \text{and} \quad \Delta\sigma_L.$$

These can be done either with a polarized deuteron beam or with a polarized deuteron target. Since pp and np elastic amplitudes have to be subsequently combined to extract the isospin components, np experiments have to be performed to an accuracy roughly comparable to that of the corresponding pp experiments.

(D) Elastic neutron-proton scattering at small t, $p_{\text{lab}} = 12 \text{ GeV/c}$.

This area is recommended for the same reason as proton-proton elastic scattering at 12 GeV/c, namely to study the energy dependence of the amplitudes. However this area should be done only after the 6 GeV/c np elastic experiments have been completed or are near completion. Similar quantities should be measured at 12 GeV/c as at 6 GeV/c ($\frac{d\sigma}{dt}$ and P are already done).

These experiments of course have to be done with the polarized deuteron target (a polarized deuteron beam provides neutrons up to only 6 GeV/c).

If there is enough time to complete these experiments for both pp and np elastic scattering at 6 and 12 GeV/c, the ZGS program will have gone a long way towards providing very substantial clues about

magnitudes, phases and energy dependences of several pure isospin amplitude pieces in nucleon-nucleon scattering.

(E) Low-energy nucleon-nucleon scattering, $p_{lab} = 1$ to 3 GeV/c.

During the last year or so, an exciting new development has taken place at the lower end of the ZGS energy range. As the beam momentum is increased above 1 GeV/c, the longitudinal total cross-section difference $\Delta\sigma_L = \sigma_{tot}(\vec{\uparrow}\vec{\uparrow}) - \sigma_{tot}(\vec{\uparrow}\vec{\downarrow})$ shows remarkable energy dependence, with a maximum difference of about -17 millibarns at a p_{lab} about 1.5 GeV/c. The transverse total cross-section difference $\Delta\sigma_T = \sigma_{tot}(\vec{\uparrow}\vec{\downarrow}) - \sigma_{tot}(\vec{\uparrow}\vec{\uparrow})$ does not show a similar structure. What causes such a large total cross-section difference $\Delta\sigma_L$? Do we finally have evidence for the first dibaryon resonance?

Theorists have of course long been interested in the possibility of a nucleon-nucleon resonance. This has either been from higher symmetry arguments [F. J. Dyson and N. H. Xuong, Phys. Rev. Lett. 13, 815 (1964) and 14, 339 (1965)] where further states are needed to accompany the deuteron; or from Regge trajectory arguments [S. Graffi et al., Nuovo Cim. Lett. 2, 311 (1969); H. Suzuki, Progr. Theor. Phys. 50, 1080 (1973) and 54, 143 (1975)]; or from breaks in the pp differential cross section at 90° [M. Libby and E. Predazzi, Nuovo Cim. Lett. 2, 881 (1969)]; or from various dynamical arguments [R. Arndt, Phys. Rev. 165, 1834 (1968); D. D. Brayshaw, Phys. Rev. Lett. 37, 1329 (1976)]. More recently, low lying six-quark entities possibly occurring in the form of dibaryon resonances, are predicted in the successful quark bag models.

Also unresolved is the structure found many years ago in the pp total cross-section σ_{tot} by Bugg et al. [Phys. Rev. 146, 980 (1966)] at a lab beam momentum of about 3 GeV/c.

A bump in a total cross-section difference of course does not necessarily mean there is a resonance lurking there--there may be none, though as we have learned from pion-nucleon scattering there may be several! In addition however, Hidaka et al. [ANL-HEP-PR-77-48] claim indications of resonant behavior from a moment analysis of the polarization data in the energy region around $p_{\text{lab}} \approx 1.5$ GeV/c. There seems every reason to be optimistic about the existence of a dibaryon resonance. But before any definite conclusions can be drawn, a very careful analysis needs to be done, in this case a proper phase shift analysis.

The TAP members thought that the ZGS could make a real and significant contribution to our understanding of nucleon-nucleon interactions in this energy range. Additional measurements should be made to enable the phase shifter to make a good analysis of the situation.

Just exactly which experimental quantities are the best ones to measure, are at present not known. There are at least two phase shift analyses (by R. Arndt and N. Hoshizaki) already started, which make use of the new $\Delta\sigma_L$ measurements. As these and other analyses progress, we envision a close interplay between theorists and experimentalists, with the theorists indicating which experimental quantities seem to be the most sensitive to the various important partial waves.

While we await these more detailed suggestions, measurements of $\Delta\sigma_T$, $\Delta\sigma_L$, C_{nn} , $C_{\ell\ell}$ and C_{ss} in this energy range should certainly be completed (some have already been done).

There is little doubt that a full understanding of what is happening in this energy range is impossible without a better knowledge of the inelastic processes that are contributing. Single pion production is copious. Moreover, the interesting region seems to be just above the $N\Delta$ threshold. It will be an extremely difficult task to sort out possible resonances and the onset of a threshold. An experimental study of Δ production processes such as

$$p\uparrow p \rightarrow n\Delta^{++}$$

or even

$$p\uparrow p\uparrow \rightarrow n\Delta^+$$

should therefore be done. The theory here is horrendous. However a start has already been made by W. M. Kloet, R. R. Silbar, R. Aaron and R. D. Amado [Phys. Rev. Lett. 39, 1643 (1977)] who use a relativistic, unitarized 3-body approach with full spinology to study both elastic and inelastic channels.

These measurements for both elastic and single pion production processes should be done first for proton-proton collisions. Should there be sufficient time, it would be very useful to make similar measurements for neutron-proton collisions.

(F) Experiments at large t , large $p_{\perp}$.

Again, during the last two years, exciting new results have been obtained as one leaves the near-forward scattering direction and looks at spin correlations at larger momentum transfers. Previously it had been expected that spin effects would become small at large momentum transfers; presumably the colliding protons (or constituent quarks) would find it harder to communicate their orientations when they scatter into larger and larger angles. Experiment however has demonstrated, through a measurement of C_{nn} , that this is not the case. C_{nn} at 11.75 GeV/c in fact does not steadily diminish with increasing momentum transfer, but oscillates and is as big as about 30% near the 90° scattering angle. Clearly some further work should be done at large momentum transfers.

The TAP members spent a great deal of time discussing the issues of large t versus the other parts of the program outlined in (A) through (E) above. At small t , some very definite statements can be made if the program is carried out, such as how nucleon-nucleon amplitudes vary with t , with energy and with isospin. The low energy investigations will undoubtedly provide information about resonance behavior. We are optimistic that definite answers will be forthcoming in these areas in the coming two or so years. It is by no means certain that this is the case at large momentum transfers. There, the theory is even less reliable. Large momentum transfer is beyond the scope of the standard Regge and geometric models. What about constituent models which are in fact geared to explain high $p_{\perp}$ collisions? Do

they apply at ZGS energies? On the one hand, it might be said that present parton models apply only to much higher energies; the approximations used in these models are not valid at ZGS energies. On the other, it can be argued that maybe parton ideas do apply (even though specific models may not); after all, the pp 90° differential cross section through the ZGS energy range does possess the s^{-10} behavior expected from parton models: [J. Gunion, S. Brodsky and R. Blankenbecler, Phys. Rev. D6, 2652 (1972); P. Landshoff and J. Polkinghorne, Phys. Lett. 44B, 293 (1973); E. Fischbach and G. Look, Phys. Rev. D15, 2576 (1977); R. Field and R. Feynman, Phys. Rev. D15, 2590 (1977); C. K. Chen, ANL-HEP-PR-77-64 and 76.]

Certainly the theoretical interpretation of the large C_{nn} values near 90° is at present unknown. However, we should probably take the attitude that new measurements here are likely to stimulate theorists into action. Other unexpectedly large spin effects are being observed at much higher energies, for example the inclusive polarization in $p Be \rightarrow AX$ at the Fermilab [G. Bunce et al., Phys. Rev. Lett. 36, 1113 (1976)], and already various quark-parton mechanisms are being proposed to explain these effects [K. Heller, UM-HE-77-38; G. Kane and Y. P. Yao, UM-HE-77-44]. While a deeper understanding of large momentum transfer spin effects at ZGS energies might take considerable time in coming, some experiments along these lines are still very worthwhile during the remainder of the ZGS lifetime.

There is of course the very practical matter involved in experiments done at large momentum transfer: because of the low

scattering rate, they take a comparatively long time to do. The Panel members were concerned that, while there is no doubt that some large momentum transfer experiments should be done, they should not take up so much running time as to seriously affect the other recommended areas of research. Given the time constraints, the weighting of the large momentum transfer work and the other areas is very delicate.

We conclude Part I of this Report with a brief look at what pieces of the nucleon-nucleon jigsaw we might hope to have in our possession by the time the ZGS ceases operation. We indicate this below.

1-3 GeV/c pp elastic, inelastic
 np elastic, inelastic:
 phase shifts; a better understanding
 of nucleon-nucleon interactions at
 these energies; any resonances?

6 GeV/c pp small t: full ampl. analysis
 np small t: some amplitudes
 isospin dependence.

large momentum transfer:
 some spin correlation
 measurements;
 how big? structure?
 partons, gluons?

NN $\rightarrow$ NN π , NAK
 : exchanges,
 dynamics involved
 NN inclusive

11.75 GeV/c pp small t: some amplitudes
 np small t: some amplitudes
 energy dependence
 isospin dependence

With this program complete, the ZGS will have provided a large amount of extremely useful data. These measurements are very important for our deeper understanding of the role of spin in nucleon-nucleon collisions, and should provide a useful guide to future theories of the strongly interacting particles.

In this part of the Report, we set out, for easy reference, several quantities that are frequently used in nucleon-nucleon scattering.

Experimental quantities and the scattering amplitudes

We start by reproducing in Table 1 the list of experimental measurable quantities $I(a,b; c,d)$ in terms of the five scattering amplitudes N_0 , N_1 , N_2 , A and π . The Table is taken from Halzen and Thomas, Phys. Rev. D10, 344 (1974). By convention, a , b , c and d refer to the polarization states of the beam, the target, the scattered particle and the recoil particle respectively.

The amplitudes N_0 , N_1 , N_2 , A and π correspond to amplitudes which, in the high energy limit, have definite quantum number exchange in the t -channel. The N_0 , N_1 , N_2 correspond to natural parity exchange, the A and π to unnatural parity exchange. More recently, the latter two amplitudes have been denoted by U_0 and U_2 respectively. The subscripts refer to the amount of t -channel helicity flip.

Sometimes the Jacob-Wick s -channel helicity amplitudes ϕ_1 , ϕ_2 , ϕ_3 , ϕ_4 , ϕ_5 are used. These are defined by

$$\phi_1 = \langle + + | \phi | + + \rangle$$

$$\phi_2 = \langle - - | \phi | + + \rangle$$

$$\phi_3 = \langle + - | \phi | + - \rangle$$

$$\phi_4 = \langle + - | \phi | - + \rangle$$

$$\phi_5 = \langle + + | \phi | + - \rangle .$$

The amplitudes ϕ_1 , ϕ_2 and ϕ_3 are not constrained to vanish in the forward direction. In terms of the ϕ 's, we have

TABLE I. The laboratory observables $I(\text{beam, target; scattered, recoil}) = I(a, b; c, d)$ 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, $\hat{l}$ is along the direction of motion, and $\hat{s} = \hat{n} \times \hat{l}$ is in the scattering plane. Since the target is at rest and $\hat{l}$ is undefined, by convention we use for the target the beam unit vectors. θ_L and θ_R are the laboratory scattering and recoil angles, respectively. The observables $I(a, b; c, d)$ are just those measured with a polarized beam scattering off of a polarized target, with second scatterings performed to analyze the polarization of the scattered and recoil nucleon. In general, given the cross sections $\sigma(\pm, \pm, \pm, \pm)$ when each initial particle is polarized and each final particle's polarization analyzed parallel (+) or antiparallel (-) to a given direction $\hat{n}$, $\hat{l}$, or $\hat{s}$, the ratio of the corresponding observable in the table to the unpolarized cross section is the ratio

$$\frac{\sum_{n_i} n_a n_b n_c n_d \sigma(n_a, n_b, n_c, n_d)}{\sum_{n_i} \sigma(n_a, n_b, n_c, n_d)},$$

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 the sums over this n_i . The vectors x , y , and z denote the center-of-mass helicity-frame directions. Their relationship to n , l , and s for each particle can be inferred from the table by noting that $I(a, b; c, d)$ is linear in its arguments: e.g., $I(\alpha s + \beta l, b; c, d) = \alpha I(s, b; c, d) + \beta I(l, b; c, d)$. The x , y , and z 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, $N_0 = \frac{1}{2}(\phi_1 + \phi_3)$, $N_1 = \phi_5$, $N_2 = \frac{1}{2}(\phi_4 - \phi_2)$, $\pi = \frac{1}{2}(\phi_4 + \phi_2)$, and $A = \frac{1}{2}(\phi_1 - \phi_3)$.

Laboratory observables	Center-of-mass observables	Exchange amplitudes
$I(0, 0; 0, 0)$	$I(0, 0; 0, 0)$	$ N_0 ^2 - 2 N_1 ^2 + N_2 ^2 - \pi ^2 + A ^2$
$I(0, n; 0, 0)$	$-I(0, y; 0, 0)$	$-2 \operatorname{Im}(N_0 - N_2)N_1^*$
$-I(0, l; 0, l) \cos \theta_R + I(0, l; 0, s) \sin \theta_R$	$I(0, z; 0, z)$	$ N_0 ^2 - N_2 ^2 - \pi ^2 + A ^2$
$I(0, l; 0, l) \sin \theta_R + I(0, l; 0, s) \cos \theta_R$	$I(0, z; 0, x)$	$-2 \operatorname{Re}(N_3 + N_2)N_1^*$
$I(0, n; 0, n)$	$I(0, y; 0, y)$	$ N_0 ^2 - 2 N_1 ^2 + N_2 ^2 - \pi ^2 - A ^2$
$-I(0, s; 0, l) \sin \theta_R - I(0, s; 0, s) \cos \theta_R$	$I(0, x; 0, x)$	$ N_0 ^2 - N_2 ^2 + \pi ^2 - A ^2$
$I(l, l; 0, 0)$	$-I(z, z; 0, 0)$	$-2 \operatorname{Re}(N_3 A^* - N_2 \pi^*)$
$I(s, l; 0, 0)$	$-I(x, z; 0, 0)$	$2 \operatorname{Re}(-A)N_1^*$
$I(n, n; 0, 0)$	$-I(y, y; 0, 0)$	$2 \operatorname{Re}(A\pi^* - N_0 N_2^* + N_1 ^2)$
$I(s, s; 0, 0)$	$I(x, x; 0, 0)$	$2 \operatorname{Re}(N_3 \pi^* - N_2 A^*)$
$I(n, 0; 0, n)$	$-I(y, 0; 0, y)$	$-2 \operatorname{Re}(A\pi^* + N_0 N_2^* - N_1 ^2)$
$I(s, 0; 0, l) \sin \theta_R + I(s, 0; 0, s) \cos \theta_R$	$-I(x, 0; 0, x)$	$-2 \operatorname{Re}(N_3 \pi^* - N_2 A^*)$
$-I(s, 0; 0, l) \cos \theta_R + I(s, 0; 0, s) \sin \theta_R$	$-I(x, 0; 0, z)$	$-2 \operatorname{Re}(-A)N_1^*$
$I(0, l; l, 0) \cos \theta_L + I(0, l; s, 0) \sin \theta_L$	$-I(0, z; z, 0)$	$-2 \operatorname{Re}(N_3 A^* + N_2 \pi^*)$
$I(n, s; 0, l) \sin \theta_R + I(n, s; 0, s) \cos \theta_R$	$-I(y, x; 0, x)$	$2 \operatorname{Im}(N_3 + N_2)N_1^*$
$I(s, n; 0, l) \sin \theta_R + I(s, n; 0, s) \cos \theta_R$	$I(x, y; 0, x)$	$2 \operatorname{Im}(-A)N_1^*$
$I(s, s; 0, n)$	$-I(x, x; 0, y)$	$-2 \operatorname{Im}(-A)N_1^*$
$I(n, s; 0, l) \cos \theta_R - I(n, s; 0, s) \sin \theta_R$	$I(y, x; 0, z)$	$2 \operatorname{Im}(A\pi^* - N_0 N_2^*)$
$-I(s, n; 0, l) \cos \theta_R + I(s, n; 0, s) \sin \theta_R$	$I(x, y; 0, z)$	$2 \operatorname{Im}(N_3 \pi^* - N_2 A^*)$
$I(l, n; 0, l) \sin \theta_R + I(l, n; 0, s) \cos \theta_R$	$I(z, y; 0, x)$	$2 \operatorname{Im}(A N_0^* + \pi N_2^*)$
$I(l, s; 0, n)$	$-I(z, x; 0, y)$	$2 \operatorname{Im}(A N_0^* - \pi N_2^*)$
$I(n, l; 0, l) \sin \theta_R + I(n, l; 0, s) \cos \theta_R$	$I(y, z; 0, x)$	$2 \operatorname{Im}(A\pi^* + N_3 N_2^*)$
$I(s, l; 0, n)$	$I(x, z; 0, y)$	$-2 \operatorname{Im}(N_3 \pi^* - N_2 A^*)$
$I(s, s; l, l) \sin \theta_L \sin \theta_R - I(s, s; s, s) \cos \theta_L \cos \theta_R$		
$+I(s, s; l, s) \sin \theta_L \cos \theta_R - I(s, s; s, l) \cos \theta_L \sin \theta_R$	$I(x, x; x, x)$	$ N_0 ^2 - 2 N_1 ^2 + N_2 ^2 - \pi ^2 + A ^2$
$-I(s, s; l, l) \sin \theta_L \cos \theta_R - I(s, s; s, s) \cos \theta_L \sin \theta_R$		
$+I(s, s; l, s) \sin \theta_L \sin \theta_R + I(s, s; s, l) \cos \theta_L \cos \theta_R$	$I(x, x; x, z)$	$2 \operatorname{Re}(N_3 - N_2)N_1^*$

$$\text{Optical theorem: } \sigma_{\text{tot}} = \frac{4\pi}{k} [I(0, 0) + P_s^{\text{beam}} P_s^{\text{target}} I(s, s) - P_n^{\text{beam}} P_l^{\text{target}} I(n, n) + P_l^{\text{beam}} P_l^{\text{target}} I(l, l)],$$

$$I(0, 0) = \operatorname{Im} N_0, \quad I(s, s) = I(n, n) = \operatorname{Im} \frac{1}{2}(\pi - N_2), \quad I(l, l) = -\operatorname{Im} A$$

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

Other notation is often used for the measured quantities. These are

Polarization P or polarization asymmetry A: $P = I(0, n; 0, 0) / I(0, 0; 0, 0)$
 $= I(n, 0; 0, 0) / I(0, 0; 0, 0)$
 $= I(0, 0; 0, n) / I(0, 0; 0, 0)$

Correlation tensor C_{ab} : $C_{ab} = I(a, b; 0, 0) / I(0, 0; 0, 0)$

Polarization transfer tensor K_{ad} : $K_{ad} = I(a, 0; 0, d) / I(0, 0; 0, 0)$

Depolarization tensor D_{bd} : $D_{bd} = I(0, b; 0, d) / I(0, 0; 0, 0)$

In particular, the R and A parameters correspond to

$$R = D_{ss}, \quad A = D_{ts}.$$

Higher spin correlation tensors H_{abd} : $H_{abd} = I(a, b; 0, d) / I(0, 0; 0, 0).$

Expressions for total cross sections are as follows:

$$\begin{aligned}\sigma_{\text{tot}}(\text{average}) &= \frac{2\pi}{k} \operatorname{Im}[\phi_1(0) + \phi_3(0)] = \frac{4\pi}{k} \operatorname{Im}[N_0(0)] \\ \Delta\sigma_T &= \sigma_{\text{tot}}(\uparrow\downarrow) - \sigma_{\text{tot}}(\uparrow\uparrow) = -\frac{4\pi}{k} \operatorname{Im}[\phi_2(0)] = \frac{4\pi}{k} \operatorname{Im}[N_2(0) - U_2(0)] \\ \Delta\sigma_L &= \sigma_{\text{tot}}(\vec{e}) - \sigma_{\text{tot}}(\vec{e}) = \frac{4\pi}{k} \operatorname{Im}[\phi_1(0) - \phi_3(0)] = \frac{8\pi}{k} \operatorname{Im}[U_0(0)]\end{aligned}$$

where k is the c.m. momentum. At $t = 0$, $N_2(0) = -U_2(0)$.

Kinematics for elastic nucleon-nucleon scattering: center-of-mass system

total c.m. energy $W = \sqrt{s}$

c.m. momentum $k = \frac{1}{2} (s - 4M^2)^{\frac{1}{2}}$

nucleon energy $E = \frac{1}{2} W; \quad E^2 = k^2 + M^2$

c.m. scattering angle θ

momentum transfers $t = -2k^2(1 - \cos \theta) = -4k^2 \sin^2 \frac{\theta}{2}$

$$u = -2k^2(1 + \cos \theta) = -4k^2 \cos^2 \frac{\theta}{2}$$

$$s + t + u = 4M^2$$

transverse momentum $p_{\perp} = k \sin \theta$

$$p_{\perp}^2 = tu/4k^2 = (-t)(1 + t/4k^2)$$

$$t = -2k^2[1 - (1 - p_{\perp}^2/k^2)^{\frac{1}{2}}]$$

With $\beta = v_{\text{cm}}/c$,

$$\beta^2 = \frac{k^2}{k^2 + M^2} = \frac{4k^2}{s}$$

$$\beta^2 p_{\perp}^2 = \frac{tu}{s}$$

Kinematics for elastic nucleon-nucleon scattering: laboratory system

$$\text{beam momentum} \quad p_{\text{lab}} = \frac{Wk}{M}$$

$$\text{total beam energy} \quad \omega_{\text{lab}} = (M^2 + p_{\text{lab}}^2)^{\frac{1}{2}} = (s - 2M^2)/2M$$

$$\text{beam kinetic energy} \quad T = \omega_{\text{lab}} - M = (s - 4M^2)/2M$$

for the recoil nucleon:

$$\text{magnitude of 3-momentum} \quad [-t(1 - t/4M^2)]^{\frac{1}{2}}$$

$$\text{total energy} \quad M(1 - t/2M^2)$$

$$\cos \theta_R = \frac{E}{k} \left(\frac{-t}{4M^2 - t} \right)^{\frac{1}{2}} = \frac{2E \sin \theta/2}{(4M^2 - t)^{\frac{1}{2}}}$$

$$\sin \theta_R = \frac{M}{k} \left(\frac{-u}{4M^2 - t} \right)^{\frac{1}{2}} = \frac{2M \cos \theta/2}{(4M^2 - t)^{\frac{1}{2}}}$$

$$\tan \theta_R = \frac{M}{E} \cot \frac{\theta}{2}$$

for the scattered nucleon:

$$\text{magnitude of 3-momentum} \quad [(-u)(4M^2 - u)]^{\frac{1}{2}}/2M$$

$$\text{total energy} \quad M(1 - u/2M^2)$$

$$\cos \theta_L = \frac{E}{k} \left(\frac{-u}{4M^2 - u} \right)^{\frac{1}{2}} = \frac{2E \cos \theta/2}{(4M^2 - u)^{\frac{1}{2}}}$$

$$\sin \theta_L = \frac{M}{k} \left(\frac{-t}{4M^2 - u} \right)^{\frac{1}{2}} = \frac{2M \sin \theta/2}{(4M^2 - u)^{\frac{1}{2}}}$$

$$\tan \theta_L = \frac{M}{E} \tan \frac{\theta}{2}$$

Conversion between $-t$ and p_1^2 at $p_{lab} = 6.0$ and 11.75 GeV/c.

For a given p_{lab} , experimental quantities are usually plotted as functions of either t or p_1^2 . In Tables 2 and 3, we have provided conversions between these two variables for the laboratory beam momenta 6.0 GeV/c and 11.75 GeV/c respectively. These two Tables may be helpful to people who are more familiar with one variable and are trying to interpret an experimental or theoretical graph expressed in terms of the other variable. For $-t$ or p_1^2 less than about $1(\text{GeV/c})^2$, these two variables are approximately equal; however, as the c.m. scattering angle approaches 90° , $-t$ and p_1^2 begin to differ by a factor of 2.

Table 2: Variation of $p_{\perp}^2$ and $-t$, at laboratory beam momentum $p_{lab} = 6.0 \text{ GeV/c}$.

$p_{\perp}^2 \text{ (GeV/c)}^2$	$-t \text{ (GeV/c)}^2$	$-t \text{ (GeV/c)}^2$	$p_{\perp}^2 \text{ (GeV/c)}^2$
0.1	0.101	0.1	0.099
0.2	0.204	0.2	0.196
0.3	0.310	0.3	0.291
0.4	0.418	0.4	0.383
0.5	0.529	0.5	0.474
0.6	0.643	0.6	0.563
0.7	0.760	0.7	0.649
0.8	0.880	0.8	0.734
0.9	1.005	0.9	0.816
1.0	1.133	1.0	0.896
1.1	1.266	1.1	0.974
1.2	1.405	1.2	1.051
1.3	1.549	1.3	1.125
1.4	1.700	1.4	1.197
1.5	1.859	1.5	1.267
1.6	2.026	1.6	1.334
1.7	2.204	1.7	1.400
1.8	2.395	1.8	1.464
1.9	2.603	1.9	1.525
2.0	2.833	2.0	1.584
2.1	3.093	2.2	1.698
2.2	3.399	2.4	1.802
2.3	3.794	2.6	1.898
2.4	4.525	2.8	1.986
2.409	4.818	3.0	2.066
		3.2	2.137
		3.4	2.200
		3.6	2.255
		3.8	2.301
		4.0	2.340
		4.2	2.369
		4.4	2.391
		4.6	2.404
		4.8	2.409
		4.818	2.409

90°

90°

Formulae: $s = 2M^2 + 2M(M^2 + p_{lab}^2)^{\frac{1}{2}} = 13.157 \text{ GeV}^2$

$k^2 = (s - 4M^2)/4 = 2.409 \text{ (GeV/c)}^2$

$p_{\perp}^2 = (-t)(1 + t/4k^2)$

$-t = 2k^2[1 - (1 - p_{\perp}^2/k^2)^{\frac{1}{2}}]$

At 90° c.m., $p_{\perp}^2 = k^2$ and $-t = 2k^2$.

Table 3: Variation of $p_{\perp}^2$ and t , at laboratory beam momentum $p_{\text{lab}} = 11.75 \text{ GeV/c}$.

$p_{\perp}^2 \text{ (GeV/c)}^2$	$-t \text{ (GeV/c)}^2$	$-t \text{ (GeV/c)}^2$	$p_{\perp}^2 \text{ (GeV/c)}^2$
0.1	0.101	0.1	0.100
0.2	0.202	0.2	0.198
0.3	0.304	0.3	0.296
0.4	0.408	0.4	0.392
0.5	0.513	0.5	0.488
0.6	0.619	0.6	0.582
0.7	0.726	0.7	0.676
0.8	0.834	0.8	0.769
0.9	0.944	0.9	0.860
1.0	1.055	1.0	0.951
1.1	1.167	1.1	1.041
1.2	1.281	1.2	1.129
1.3	1.396	1.3	1.217
1.4	1.513	1.4	1.304
1.5	1.631	1.5	1.390
1.6	1.751	1.6	1.474
1.7	1.872	1.7	1.558
1.8	1.996	1.8	1.641
1.9	2.121	1.9	1.723
2.0	2.248	2.0	1.804
2.2	2.509	2.2	1.962
2.4	2.779	2.4	2.117
2.6	3.060	2.6	2.268
2.8	3.352	2.8	2.415
3.0	3.657	3.0	2.558
3.2	3.977	3.2	2.697
3.4	4.314	3.4	2.832
3.6	4.672	3.6	2.963
3.8	5.055	3.8	3.091
4.0	5.470	4.0	3.214
4.2	5.924	4.4	3.449
4.4	6.433	4.8	3.668
4.6	7.022	5.2	3.872
4.8	7.749	5.6	4.060
5.0	8.826	6.0	4.232
5.090	10.180	6.4	4.388
		6.8	4.529
		7.2	4.654
		7.6	4.763
		8.0	4.857
		8.4	4.934
		8.8	4.996
		9.2	5.043
		9.6	5.073
		10.0	5.088
		10.180	5.090

90°

90°

Formulae:

$$s = 2M^2 + 2M(M^2 + p_{\text{lab}}^2)^{\frac{1}{2}} = 23.881 \text{ GeV}^2$$

$$k^2 = (s - 4M^2)/4 = 5.090 \text{ (GeV/c)}^2$$

$$p_{\perp}^2 = (-t)(1 + t/4k^2)$$

$$-t = 2k^2 [1 - (1 - p_{\perp}^2/k^2)^{\frac{1}{2}}]$$

At 90° c.m., $p_{\perp}^2 = k^2$ and $-t = 2k^2$.

Conversion between laboratory beam momentum, laboratory beam kinetic energy and the total center-of-mass energy.

At lower energies where there is the possibility of a dibaryon resonance, it will be necessary to study the data in terms of nucleon-nucleon phase shifts. Expansions of the helicity amplitudes in terms of phase shifts have been written down by G. Thomas in the Kane 1975 Report, and we refer the reader to this article (and the references cited therein) for the various formulae. One problem that the present Panel kept running into was the fact that nucleon phase shifters usually use the laboratory beam kinetic energy T (in MeV), whereas high energy workers usually use the laboratory beam momentum p_{lab} (in GeV/c). To help alleviate the confusion over this problem, we provide Table 4 and a graph to show the relation between p_{lab} and T , together with the total c.m. energy W , for values of the variables in the possible dibaryon resonance region.

Table 4: Laboratory beam momentum p_{lab} in GeV/c, laboratory beam kinetic energy T in MeV, and the total c.m. energy W in MeV.

p_{lab} (GeV/c)	T (MeV)	W (MeV)
0.5	124.9	1938
0.6	175.4	1962
0.7	232.3	1989
0.8	294.7	2019
0.9	361.9	2049
1.0	433.0	2082
1.1	507.5	2115
1.2	585.0	2149
1.3	664.9	2184
1.4	747.0	2219
1.5	831.0	2254
1.6	916.5	2289
1.7	1003.5	2325
1.8	1091.6	2360
1.9	1180.8	2395
2.0	1270.9	2430

Formulae:

$$T = (M^2 + p_{lab}^2)^{\frac{1}{2}} - M$$

$$W^2 = 2M^2 + 2M (M^2 + p_{lab}^2)^{\frac{1}{2}} = 4M^2 + 2MT.$$