PROGRESS REPORT ON CONTRACT NO. AT-(40-1)-3509, November, 1973

TITLE: Elementary Particle Physics at The Florida State University

ORO-3509-10

This report covers the twelve-month period from November 1, 1972 to October 31, 1973. We summarize here the highlights of the progress. For the second year in a row we exposed half a million bubble-chamber pictures; this year all of them were taken at Stanford at the 82-inch bubble chamber. We participated in running an experiment and in design of equipment at NAL. Our group served as the host for an international conference on ππ scattering. The theoretical research was expanded into a new topic with the addition of P.A.M. Dirac to the contract. Theoretical efforts at studying the absorption model and other production mechanisms came to fruition with the publication of a large number of papers.

I. Logistics

A. Personnel

Theoretical research in our group expanded into a new area with the addition of P.A.M. Dirac to the contract. He has been on the FSU faculty for several years, and beginning August of 1973 he joined the research effort in particle physics. Robert Lind came here from Temple University in September of 1973 to work as a research associate with Dirac.

During this report period Kimel and Williams were promoted to associate professor positions. Both of them, along with V. Hagopian, were granted tenure.

At the end of the summer of 1973 Ewald Reya left our theory group to accept a faculty position at Mainz, Germany. His research associate position here was filled in September by Lawrence Thébaud, who was previously at the University of Arizona.

Several changes have occurred among the experimental graduate students. Norberto Ezquerra joined our group. William Morris completed his Ph.D. (see Enclosure D.1) and accepted a position as a research associate at Michigan State University. Richard Wieckowicz also completed his Ph.D. in June (see Enclosure D.2); he is now working for the Department of Transportation of the State of Florida.

B. Facilities

During the period covered by this report we improved our facilities primarily by adding to our EMR 6050 computer and to our image-plane digitizers (IPD's).

We purchased a sense-and-signal line option ($2000) and a new card reader ($3400; 1000 cards/min) with state funds. We also acquired two surplus drum storage units, one of which will be cannibalized to renovate the other; the renovated drum will be installed on our 6050 to use as insurance against the possible failure of the existing drum.

Interfaces between two IPD's and the 6050 were completed and debugged. Two additional interfaces are built and await the arrival of their digitizing arms for further testing. The first of these two arms is on order, using both AEC and state funds. The next arm will have its major components bought with state funds and the rest fabricated at FSU.

A Tektronix 4010 termal was leased and is now being used to provide human intervention in problems of pattern recognition for complicated events measured on automatic machinery (see Enclosure [illegible]). This device has been interfaced both to the EMR 6050 and to the CDC 6500, the campus computer.

II. Experimental Research Program

A. π^+d at 15 GeV/c

The objective of this experiment is to study production and decay mechanisms of multiparticle final states, both strange and non-strange. This experiment features high energy, high resolution and high statistics. It is divided into two parts.

Part (1) By May of 1972 about 350,000 useful pictures were obtained at the SLAC 82-inch bubble chamber with about 8 beam tracks per picture. By October of 1972 all the non-strange particles that we plan to study from this film were scanned, measured on the flying spot digitizer (HPD) at the University of Pennsylvania and processed through a series of pattern-recognition programs. The output of this sequence was suitable as input to a geometric reconstruction program. During February of 1973 we redigitized those events that had failed during the first pass - about 10% of the sample. About 50,000 non-strange events were measured in all. This part of the experiment was a joint effort by our group and J. Bensinger, formerly at the University of Pennsylvania.

In addition about 10,000 events involving strange particles are being measured at FSU by conventional measuring machines. This phase is about 60% complete.

Part (2) As a consequence of the results of the first part of this experiment, in May 1973 we requested from SLAC another 500,000 photographs of π^+d at 15 GeV/c. This proposal was approved, and 520,000 additional photographs were obtained during September and October 1973. At the present time the film is being developed and we should receive it soon. This part of the experiment is a collaboration with the University of Tennessee and Oak Ridge National Laboratory. The present plan calls for processing the photographs at FSU with the exception of measurement, which will be done at Oak Ridge on the University of Tennessee Spiral Reader. As specific progress for this part we have adapted the Lawrence Berkeley Laboratory Spiral Reader pattern recognition computer program, called POOH, and on a test roll from the film of Part (1) we have managed to reconstruct events with an efficiency better than 63%. We are now in the process of fine tuning this program and hope to be able to improve the efficiency to better than 80%.

The experiment is now at the stage where we can begin to ask physics questions of the data referred to in Part (1). About a month ago we obtained data summary tapes that include ionization information. About 30% of the measured events failed somewhere in the process of data reduction. To try to resurrect most of these failed events a computer program was written to enable an operator to display the measured information on a CRT (Tektronix 4010) connected on-line to a computer (either the CDC 6500 or the EMR 6050). The operator compares the CRT display with the projection of the film and can modify the display by typing instructions on the 4010. On a test roll of film we were able to save 2/3 of the failed events. We plan to put this procedure into full production within the next few weeks. A report on the system was presented at the 1973 Washington meeting (see Enclosure A.2d). Another part of the data reduction that required much effort was the improvement in TVGP (three-view geometry program) so that a version including trackmatch would accept measurements from the HPD. This effort required recoding of parts of TVGP.

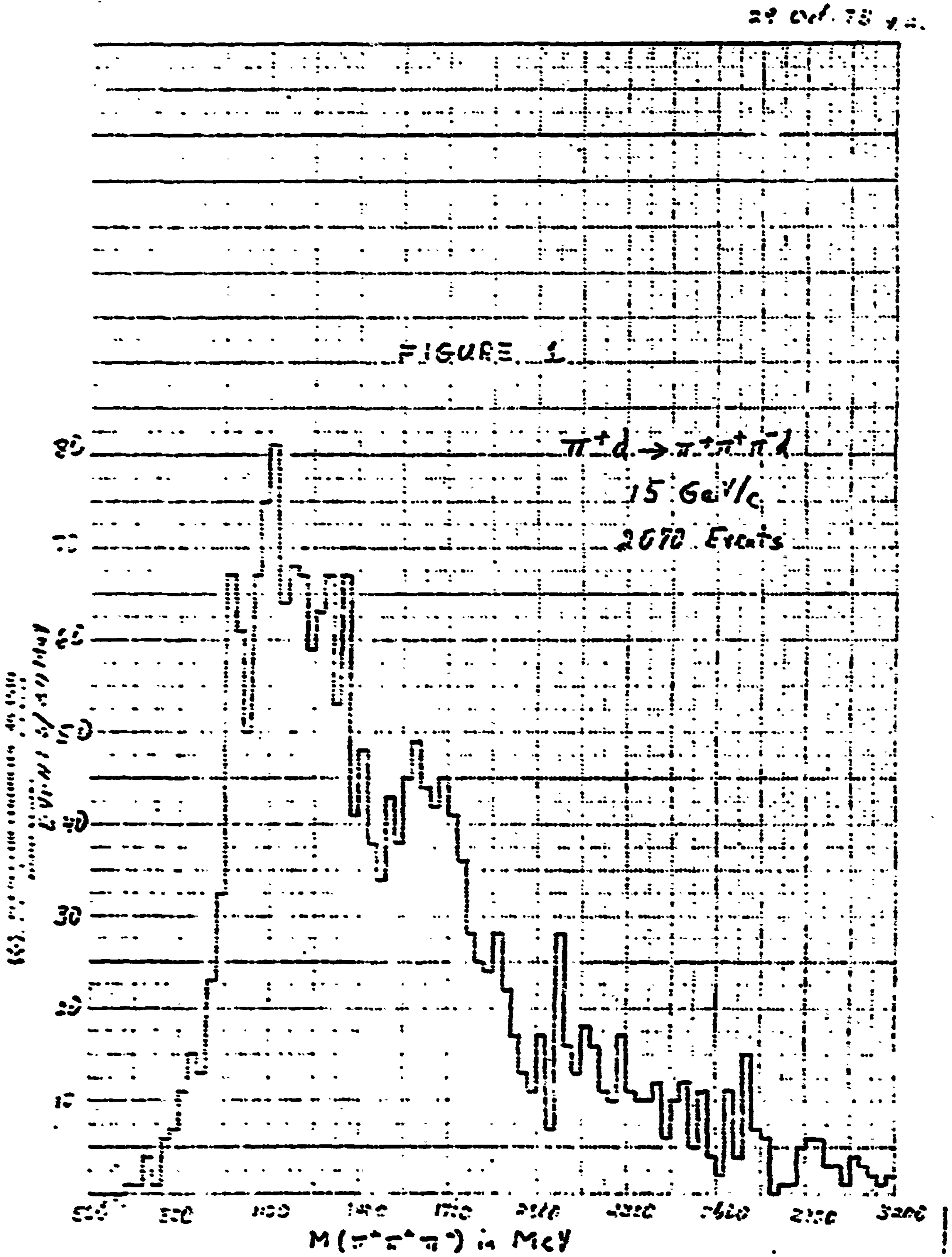
Much effort in this experiment has gone into the substantiation of the claim to high accuracy. The measurement process with the HPD is very accurate. The optical constants have been calculated well enough to match this precision and produce small errors on the final results. For example, four-constraint events have mass errors of 5 to 10 MeV; one-constraint events have errors about twice as large. The missing-mass spectrum from $\pi^+d \to pp\pi^+\pi^-$ + (missing mass) shows a peak of width equal to 0.03 $(GeV)^2$ corresponding to the π^0 - a result better than those obtained from most other bubble-chamber experiments at comparable energies.

Among the non-strange events we measured topologies with 2 through 8 prongs with a track identifiable as a deuteron or a proton. We summarize some of the physics results already obtained.
$\underline{\pi^+d \to \pi^+\pi^+\pi^-d}$ About 2000 events have already been identified. Fig. 1 shows the 3π mass spectrum. The A_1 associated with $\rho \to \pi^+\pi^-$ and the A_2 associated with $f \to \pi^+\pi^-$ are clearly visible. We do not have any evidence for the $g\pi$ resonance near 1900 MeV claimed by Lubatti _et al._, although our data are compatible with a 3π resonance at 2100 MeV. Another interesting case is the $d\pi$ mass combination where we see the well known d* resonance at 2200 MeV in both $d\pi^-$ and $d\pi^+$ final states. In addition in the $d\pi^-$ final state we see a resonance of 4.5 standard deviations with $\Gamma<100$ MeV at 2900 MeV. (See figure 2). The existance of a d* is interesting and needs to be studied in detail. For example, does each N* or Δ have a corresponding d*? This could shed some light on the structure of the deuteron and from there to all other complex nuclei. A report on this reaction has been given at an APS meeting. (See Enclosure A.1c).

We also have events with final states containing 4 or more pions and an intact deuteron. So far we have not studied these final states in detail but hope to do so in the next several months.

Possible Evidence of $\Delta\Delta(1236)$ Component in the Deuteron

Upon the suggestion of Dr. Maurice Goldhaber of BNL we looked for the possible existance of $\Delta\Delta$ in our data. The evidence comes from the fact that about 1% of the time when the π^+ collides with the deuteron a slow $\Delta(1236)$ is left behind in the laboratory system. An intriguing interpretation is that the deuteron was composed of $\Delta\Delta$ instead of np for ~1% of the time and the collision left one of the Δ's as spectator. This idea has created a lot of interest in conferences during summer of 1973, and since then other groups have also looked at their data with essentially the same results. FSU physicists met at Berkeley with physicists from Cal. Tech, LBL, University of California at Berkeley and University of Washington, in Seattle to compare the data and came to the conclusion that all other possible dynamical and kinematical interpretations have to be studied before we can positively say that what we



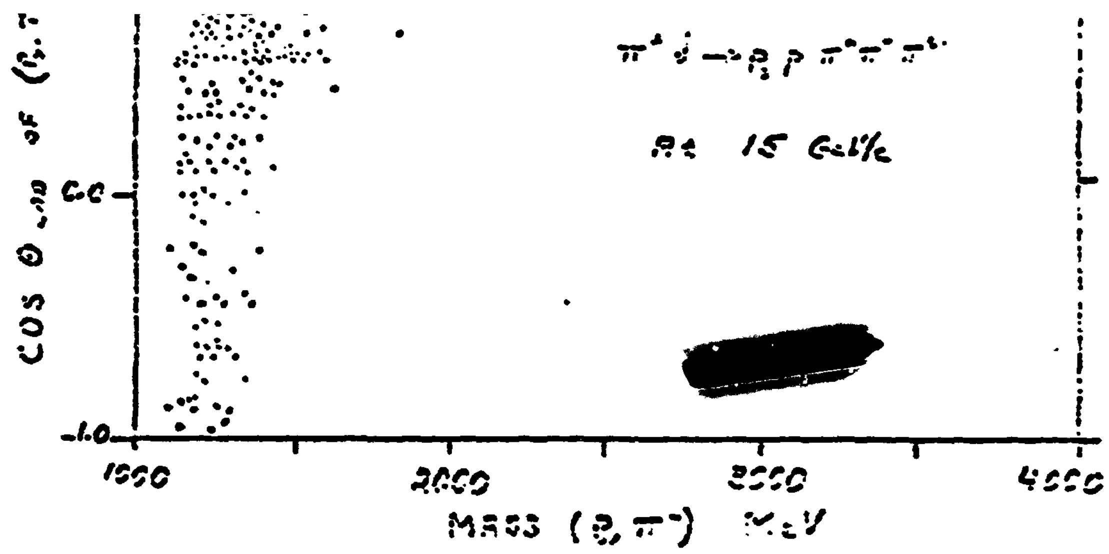


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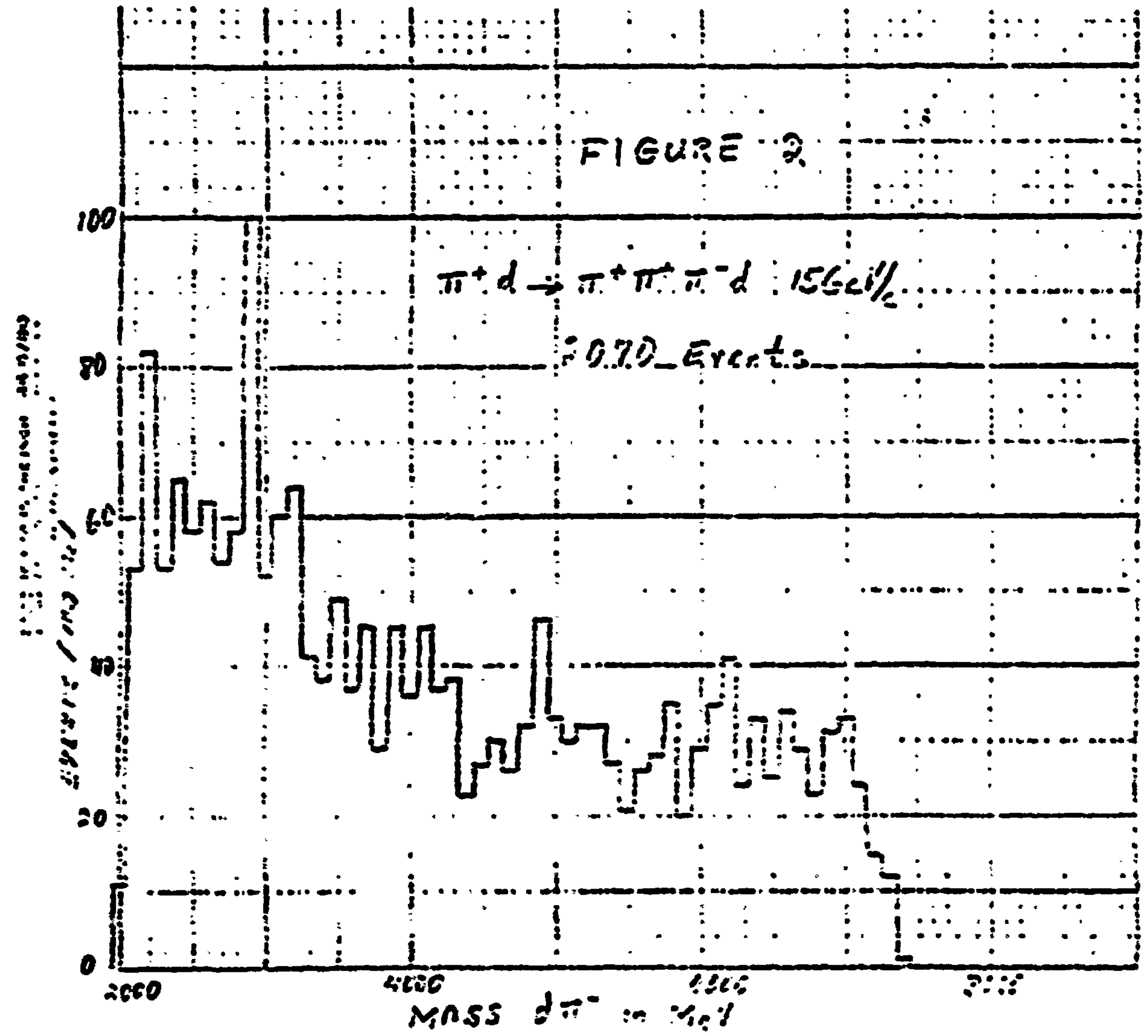
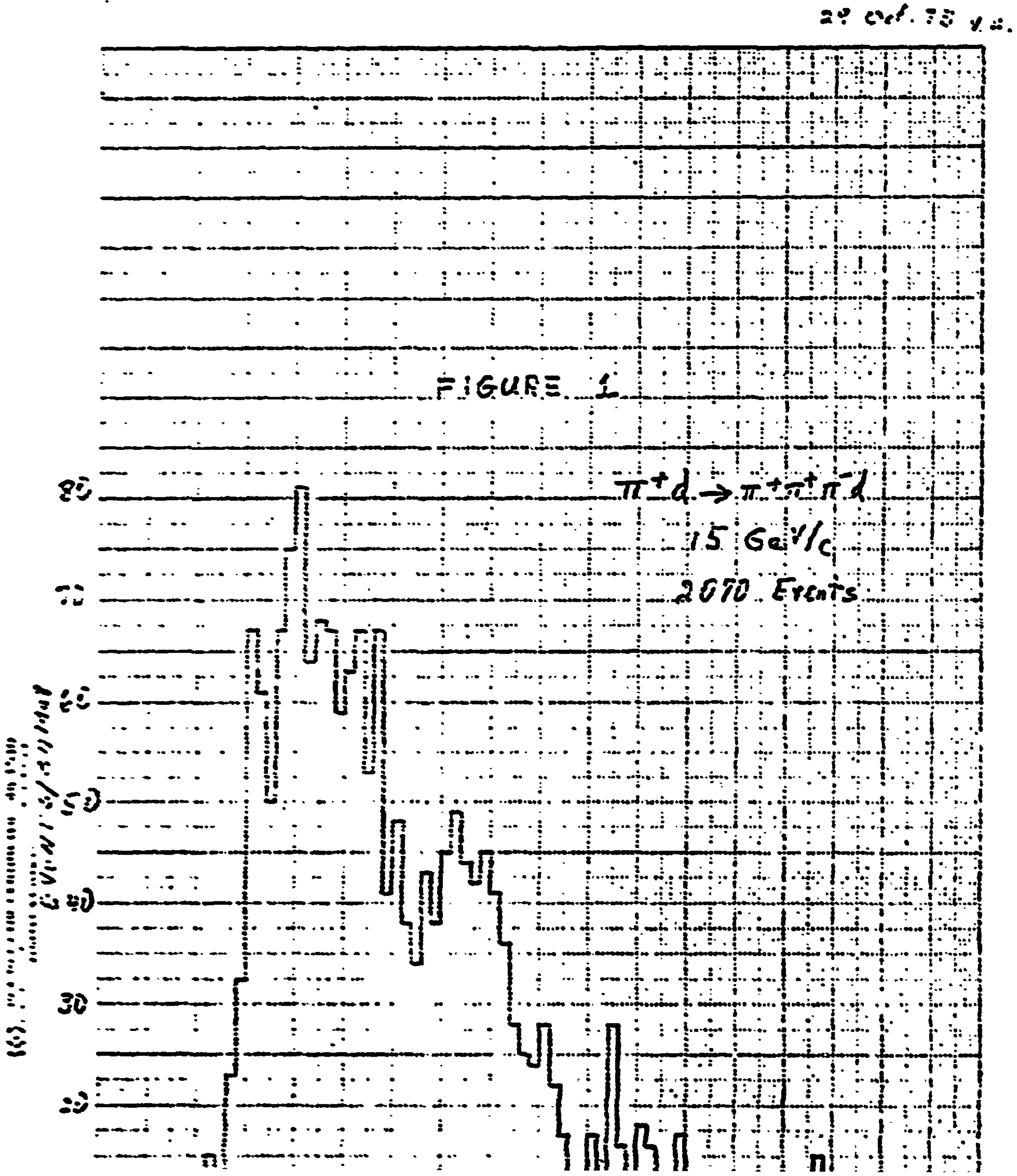
FIGURE 3





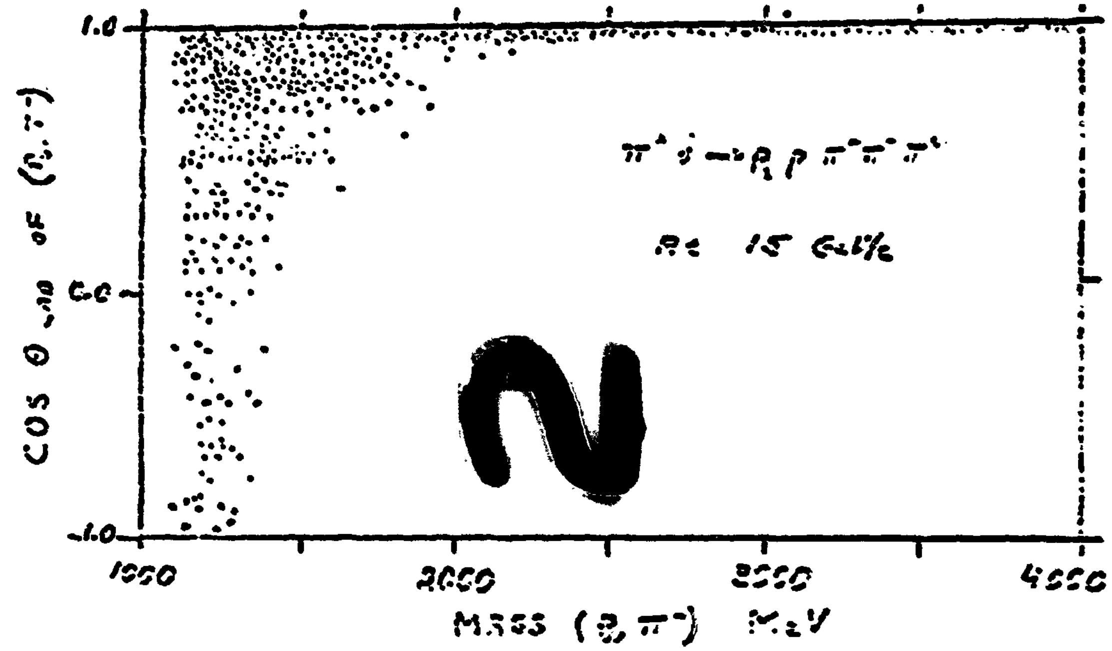


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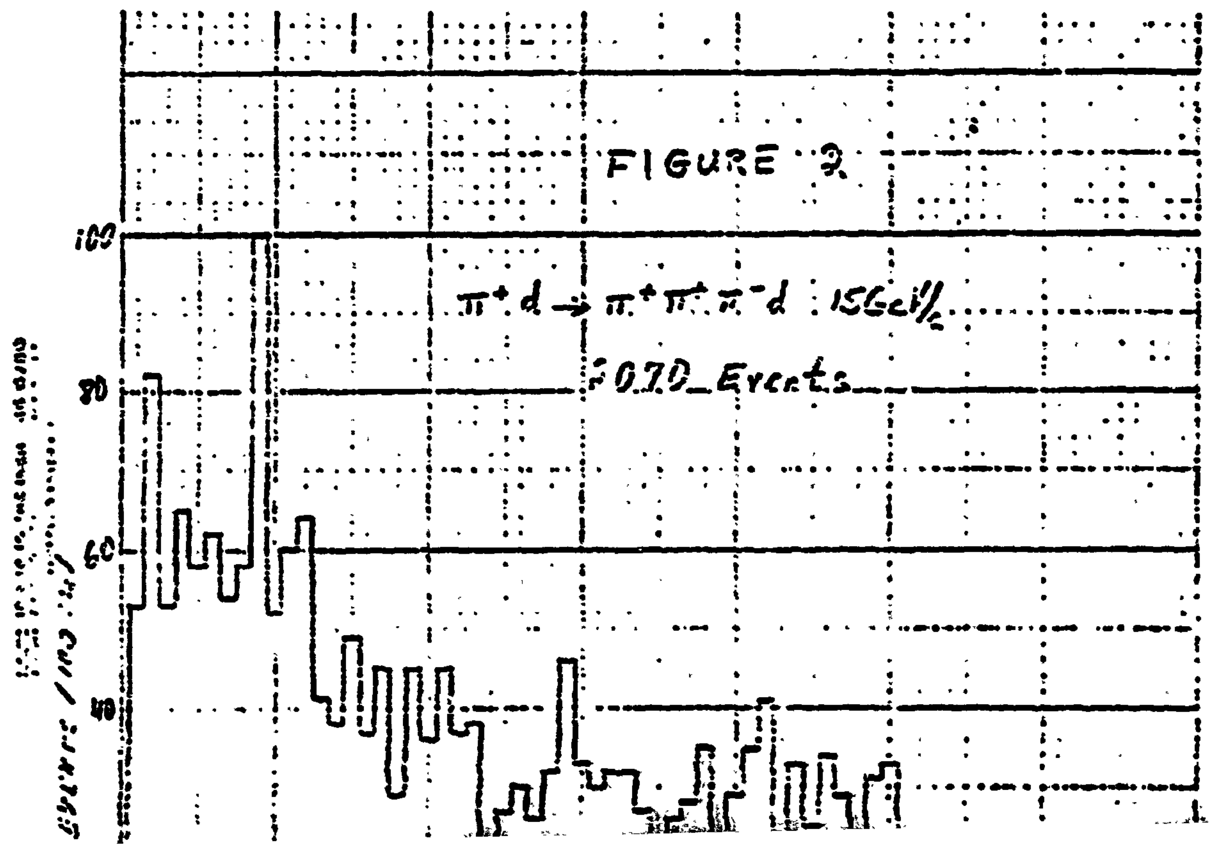
FIGURE 3



are seeing is a $\Delta\Delta$ component of the deuteron. Figure 3 shows the plot which suggests the $\Delta\Delta$ existance, namely Mass($p\pi^-$) vs. cos θ where θ is the laboratory angle of the $p\pi^-$ with respect to the incoming π^+. The backward events at the $\Delta(1236)$ mass are the events that can be assumed to be spectators. Attached are several reports at various conferences and one by Allan Bromley to AIP which discuss our data (see Enclosures F.1 and F.2).

$\pi^+ + n \rightarrow \pi$'s $+ p$

The interactions with the neutron as a target and the proton as spectator have been studied in some detail. A few of the reactions where we have good data are $\pi^+n \rightarrow \pi^+\pi^-p$, $\pi^+n \rightarrow \pi^+\pi^-\pi^0p$, $\pi^+n \rightarrow \pi^+\pi^+\pi^-\pi^-p$, $\pi^+n \rightarrow \pi^+\pi^+\pi^-\pi^-\pi^0p$ and $\pi^+n \rightarrow \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-p$. We see most of the known resonances that can be formed. The data are still being analyzed to clarify as much as possible the ambiguous events and we are presently hard at work to improve our data samples. A report was given at an APS meeting on these reactions. (See Enclosure A.1d).

Strange Particle Production

We are currently measuring all double V events and also 2,3 and 4 prong events with an identifiable proton or deuteron and one V. The measurements are 60% completed. We will study such final states as $K^0\bar{K}^0$, ΛK, $K^0\pi$ etc. Since the events are in the measuring stage we do not report on any results. (V. Hagopian, S. Hagopian, Horne, Pewitt, Wind, Wilkins, Albright and Lannutti).

B. K^-d From 470 to 850 MeV/c

In the years from 1967 to 1971 we obtained 537,000 pictures of K^-d at the 30-inch bubble chamber at BNL. During the period covered by this report we completed the last of the scanning for events in the two-prong V topology in the most recent exposure and have begun to measure them.

Results on various portions of the analysis have been produced and disseminated. We summarize briefly the progress.

In the higher momenta we have been analyzing data on $K^-n \to \Sigma\pi\pi$. Results show the expected $\Sigma(1660)$ in the $3/2^-$ wave, and we are studying ambiguities in other partial waves and the competing processes $\Sigma(1660) \to \Sigma(1385)\pi$, $\Lambda(1405)\pi$ and $\Lambda(1520)\pi$ (see Enclosures A.1g, B.1 and E.2).

At a momentum setting of 727 MeV/c we studied the one-prong and two-prong events with no obvious hyperons. Results on K^-d elastic scattering and $K^-d \to K^-np$ have been presented (see Enclosures B.9 and D.2).

At all momenta we are studying $K^-n \to \Lambda\pi$ and $\Lambda\pi\pi$. During this report period we presented results on these final states for momenta of 575 and 630 MeV/c. These results seem to point toward favoring the existence of a $\Sigma(1620)$ state, but are being studied more carefully before submission for publication (see Enclosures A.2 and D.1). (Albright, Colleraine, Lannutti, Richey, Ezquerra, Morris, Wieckowicz).

C. Beam Design at NAL

During the summer of 1973 one of us worked at NAL on the problem of building a beam to transport hadrons to the 15-foot bubble chamber. There were several purposes involved in this activity: to provide help for NAL to work on a project for which they could not spare people; to gain experience toward future design of a K_L^0 beam for an experiment we propose to do at NAL; to implement the recommendations of Section V-1 of the HEPAP report "encouraging physicists to spend time at a national laboratory during formative stages of the development of its research facilities;" and to speed up the program of experiments for the 15-foot bubble chamber.

These purposes were accomplished. The N5 beam design was completed, components placed and instrumentation ordered. In October of 1973 a trial tune-up took place using the preliminary instrumentation as available then. The N5 beam successfully transported protons at 300 GeV/c in that test. Later it transported π^- at 50 GeV/c. (Lannutti).

D. pp Scattering at NAL

During the summer and Autumn of 1973 A. P. Colleraine has been collaborating with the Rutgers group on experiment #67 at NAL. This experiment uses the H_2 gas jet at the C-zero internal target laboratory in the main ring of the accelerator. It is in essence a missing-mass experiment in which the reaction is $pp \rightarrow p+X^+$; by using a counter telescope to measure the properties of the proton in the final state, one can compute the mass of the X^+. Experimental spectra for the missing mass and for the momentum transfer to the proton have been obtained. The numbers are on data summary tapes, and the results are being made ready for publication. (Colleraine).

E. Migma Physics

In March 1972 A. P. Colleraine took a six-month leave of absence from FSU to continue work with B. Maglich on the experimental and theoretical aspects of the Rutgers Migmacell. After his return to FSU he made trips once a month to Rutgers (paid for by Rutgers Migma group funding) to complete the summer studies. As of December 1972 we had not succeeded in storing a complete 360° migma profile because of continued problems with the electrostatic inflector. Indications were, however, that sufficient intersecting loops were passing through the central high-density core to allow the self-colliding properties of the orbits to be studied. Subsequent investigation (in which Colleraine was not directly involved) showed that by August of 1973 deuteron fusions were indeed occurring, and their products, tritium and He^3 could be readily detected with solid state counters and pulse height analysis. Some further studies of the space-charge problem in a migmacell were brought to a conclusion by February 73 (see Enclosures A.1e, A.1f, A.2b and A.2c) (Colleraine).

F. π^+p at 11 GeV/c

This experiment was completed some time ago. During this report period one paper was published (see Enclosure B.8). (Lannutti, Albright).

G. The Study of the Reaction $\pi^\pm d \rightarrow (m\pi)^\pm d$, m=1,2,3,...6 Using the MPS at Brookhaven National Laboratory.

One member of our group spent five weeks during the summer of 1973 as a guest collaborator with the Lindenbaum-Ozaki group at Brookhaven National Laboratory. There we explored the feasibility of using the Multiparticle Spectrometer (MPS) to study coherently produced pions from deuterons. (i. e. interactions in which the deuteron does not break up). This is an extention of our study of π^+d reactions at 15 GeV/c.

For coherent reactions the MPS is ideally suited, since the triggering is very simple. Calculations performed at both BNL and FSU convinces us that a proposal should be submitted to BNL. A letter of intent was given to Dr. R. R. Rau of Brookhaven National Laboratory (see Enclosure G.1). Details of the experiment together with copies of the proposal are in next year's proposal to the A.E.C. and will not be discussed here. (V. Hagopian).

H. π-π Scattering

Since the last progress report, more work has been carried out in studying the reaction $\pi^-p \rightarrow \pi^-\pi^+n$. Some of this work was in conjunction with the π-π Scattering Conference that we hosted at our University during March 1973. With higher statistics available now, the field of π-π scattering is getting renewed attention. One of the most troublesome assumptions made by many physicists is that the extrapolated cross section for the reaction $\pi N \rightarrow \pi\pi N$ is zero at t=0. (t is 4-momentum transfer squared to the nucleon). We show that this assumption is incorrect for the data of $\pi^-p \rightarrow \pi^-\pi^+n$ at 2.3 GeV/c. We also show that based on the absorption model of the one pion exchange, the calculated results agree with our experiment and also show that the cross section at t=0 is non-zero for almost all beam momenta (see Enclosure B.7). S. Hagopian, D. Pewitt, V. Hagopian). A paper has been published (PR).

The data from $\pi^-+p \rightarrow \rho^0+n$ and $\pi^-+p \rightarrow \rho^-+p$ at 2.3 GeV/c are consistant with a dip in $d\sigma/dt$ at $t\sim -0.6$ $(GeV/c)^2$ for ρ^- production and a break at $t\sim -0.6$ $(GeV/c)^2$ for ρ^0 production, in agreement with theoretical predictions based on the Regge pole model and consistant with other experiments. A paper has been published in the Proceedings of the π-π Conference and details can be found in a review talk by J. Matthews in the same proceedings (see Enclosure B.10). (S. Hagopian, V. Hagopian).

I. The Mass of the Neutrino

A feasibility study was performed to determine whether a better mass measurement of the υ_μ using the reaction $\pi \rightarrow \mu+\upsilon$ could be made. The present limit of the υ mass is less than 0.7 MeV. It was determined that using the LAMPF facility at Los Alamos the error of the mass of $\upsilon\mu$ can be reduced about 100 times if the pion mass is known as well as the muon mass. A proposal to perform this experiment was not submitted at this time. When the pion mass is better determined we could then submit the proposal to LAMPF. (V. Hagopian, Richey, Ezquerra).

J. Software for Pattern Recognition

1. Pattern Recognition Program POOH Used for Spiral Reader Measurements

During September 1973, 520,000 photographs of SLAC 82-inch bubble chamber were taken. The events (~50,000) will be measured on the University of Tennessee Spiral Reader located at Oak Ridge National Laboratory. To reduce the measurements the track following-pattern recognition program POOH written at Lawrence Berkeley Laboratory was converted to our CDC 6500 computer. The basic conversion was easy and accomplished in two weeks. A sample roll was measured and the measurements passed the data-reduction process with 63% efficiency. At present the failures are being studied to maximize the efficiency of the track-following-pattern-recognition program POOH. This program takes about 8 seconds to reduce an event for suitable input to the geometry program. As an aid for the debugging process a TEKTRONIX 4010 CRT display is being utilized.

It is appropriate to mention that, since our computer is a CDC 6500, we are able to transport and use programs from LBL and BNL with few problems For example, the plotting program from LBL called ERGON was converted to our computer in one week. (S. Hagopian).

2. Development of a CRT Display Program to Resurrect Failed Events

An interactive graphics program RESURX has been coded which allows for human interaction to resurrect events which otherwise would have failed the data reduction process. For the 15 GeV/c π^+d bubble chamber experiment about 30% of the events that were measured on the University of Pennsylvania Flying Spot Digitizer (HPD) failed to pass all the way to post kinematics program. These events failed for various reasons and about 60% of the failed events still had enough information to give all the needed physics results, namely four vectors for each particle. A computer program was written to use a TEKTRONIX 4010 CRT display system on line with our CDC 6500 computer to display the tracks as measured by the HPD. An operator compares this display with the bubble chamber photographs, by use of the TEKTRONIX keyboard eliminates extraneous tracks, fixes all other possible errors, trackmatches among the 3 views and sends this resurrected event to geometrical reconstruction. A small sample has already been resurrected in this fashion and we expect to complete the rest in about four months.

This program is written mostly in FORTRAN and is easily transportable to any other computer with 24 or more bits per word. This program is written in a flexible manner so that it can easily be adapted to display a variety of information. This flexibility has turned out to be very useful in debugging pattern recognition programs. (Pewitt).

K. Computational Methods

During this report period work has continued on problems related to Monte Carlo simulation of high-energy processes. Papers in this area have been produced (see Enslosures B.17, E.3 and E.4). Recently these methods have been brought to bear on problems related to the $\Delta\Delta$ discussed in section A above. Specifically one can use Monte Carlo to investigate whether or not it is possible to explain the data of the π^+d experiment without invoking the process $d \to \Delta\Delta$.

As a result of our unsuccessful attempt to get approval for an experiment to study muonic decays of the Σ^- hyperon, it was discovered that the turning angle of a charged particle's orbit in a uniform magnetic field is an excellent estimator of its momentum, even in the presence of momentum loss and of optical distortion. The results of this discovery have been published (see Enclosure B.16). (Knop).

III. π-π Scattering Conference

On March 28, 29 and 30, 1973 an international conference on "π-π Scattering and Associated Topics" was hosted by us at FSU. The participants included roughly half the physicists actively working on this subject in the world. We had good representation from both CERN and Munich, who have some of the major results in π-π and K-π scattering. The conference included 18 invited papers, 13 contributed papers and two panel sessions. The proceedings of this conference were edited by P. K. Williams and V. Hagopian and published by the AIP as part of their conference proceedings series. Since we are not including copies of the proceedings, we have attached copies of the preface and table of contents (see Enclosure C.1).

The only other topical conference on a similar subject was held at Argonne National Laboratory during May of 1969. At that time π-π and K-π data had just become available, mostly from bubble chambers. The Conference was a comprehensive one and proceedings were distributed by ANL. Since 1969, several experiments with very large statistics have been completed, including the CERN-Munich 17 GeV/c experiment and the SLAC 15 GeV/c experiment. Several more are in various stages of progress at Argonne, CERN and SLAC. Others are in planning stages. In actuality we heard some of the most recent results of the Argonne experiment for the first time during this conference.

It was a most appropriate time to discuss these large experiments with special emphasis on the analysis of the data, including uses of absorption models and amplitude analysis. The invited and contributed talks were evenly divided between theory and experiment. Results of π-π and K-π phase shifts were reported. Also there were some discussions about future directions of the experimental program. For example polarized targets will be very useful in studying π-π scattering and also extensions to both high t and higher values of π-π mass.

Several of us at FSU have been quite active in π-π and K-π scattering work, both theoretically and experimentally. This was the reason of holding the conference at FSU. Financial support came from FSU, NSF and AEC. The conference chairman was P. K. Williams assisted in all aspects by V. Hagopian.

IV. Theoretical Research Program

A. Models and Amplitude Analysis For Three-Body Final States

During the past year we have been particularly concerned with the reactions $\pi p \rightarrow \pi\pi N$ and $Kp \rightarrow K\pi N$. These three-body final state reactions are interesting not only because of the relative simplicity of their production mechanism (which is dominated at small $|t|$ by absorptive π-exchange) but also because of the widespread interest they enjoy experimentally due to the possibility these reactions hold for the measurement of $\pi\pi$ and $K\pi$ phase shifts. An investigation of the production mechanisms for these reactions is equivalent to formulating an extrapolation procedure for extracting $\pi\pi$ and $K\pi$ phase shifts. Our program began with the construction of a generalized absorption model for π-exchange which could, upon varying the three parameters, reproduce all of the numerous popular formulations of absorptive π-exchange as well as take into account coherent background from other exchange mechanisms in the small $|t|$ region. Our description of the 15 GeV/c SLAC data on $\pi^- p \rightarrow \pi^-\pi^+ n$ (see Enclosure B.2) also the reactions $K^- p \rightarrow K^-\pi^+ n$ and $K^+ n \rightarrow K^+\pi^- p$ (see Enclosure B.4) was quite good, both as to production and to decay properties, showing the substantive validity of absorptive π-exchange as we had formulated it. Later, when the amplitude analysis of Estabrooks and Martin using the CERN-Munich data on $\pi^- p \to \pi^- \pi^+ n$ at 17.2 GeV/c became available, we were able to compare our model amplitudes directly with the experimental ones, again with quantatively good results (see Enclosure B.5). It became apparent that the advent of the CERN-Munich experiment, a super-high statistics experiment covering the broad t-range up to -1 $(GeV/c)^2$, would make possible a study of A_2 exchange constrained much more strongly by accurate data than previously. In work (see Enclosure B.3) which again made use of the amplitude analysis of Estabrooks and Martin, we were able to establish the presence of substantial A_2-exchange contributions, even in the near forward direction where it had previously been neglected in analyses of $\pi\pi$ scattering.

In speaking of the amplitude analysis of Estabrooks and Martin, we should more accurately call their work a "partial" amplitude analysis in that it allows certain discrete ambiguities. Thus we were led to the problem of formulating a complete amplitude analysis for any reaction of the form $0^- + \frac{1}{2}^+ \to 0^- + 0^- + \frac{1}{2}^+$, delineating the new information which can be obtained from target- (or recoil -) nucleon polarization measurements (see Enclosure B.14). Minimum measurements required for a unique amplitude analysis were determined from a graphical technique. Finally the relevance of our amplitude analysis to the measurements of π-π phase shifts was summarized at the Tallahassee Conference (see Enclosure B.12). (Kimel, Reya).

B. Chiral Symmetry Breaking and Meson - Nucleon Sigma Commutators

For some time it has been apparent that strong interactions are approximately SU(3)-symmetric. Recently Gell-Mann suggested that strong interactions are nearly symmetrical under the bigger group SU(3) x SU(3) generated by the algebra of the vector and axial-vector currents of the hadrons. The idea that strong interactions are almost SU(3) x SU(3)-symmetrical appears to be the only rational way in which one can understand the joint successes of current algebra and partially conserved axial-vector current (PCAC). For the real world chiral symmetry breaking has to occur in order to generate appropriate (not mass degenerate) SU(3) multiplets of particles and also eight low-mass mesons, π, K, and η which satisfy an approximate PCAC condition. The most elegant and physically plausible model of breaking chiral symmetries is the $(3,\bar{3})+(\bar{3},3)$ model of Gell-Mann Oakes, and Renner (GMOR).

The physical effects most sensitive by far to the symmetry breaking mechanism are corrections to low-energy theorems. Of particular importance are the σ-terms which provide crucial information about the nature of chiral symmetry breaking and what symmetry breaking mechanisms should be used. With the exception of the work of Cheng and Dashen, most workers find that the σ-term in πN scattering is compatible with the GMOR model although the values obtained are slightly enhanced over the pure GMOR predictions.

We have tried to obtain σ-terms and test the GMOR model for reactions other than πN scattering, namely for KN scattering. Last year's progress report discussed our results based on a dispersive approach. During the past year we have applied an independent approach based on Weinberg's smoothness hypothesis. In our letter (see Enclosure B.15) we obtained a σ-term rather compatible (with a factor of 2) with the GMOR model of symmetry breaking. We later expanded this work (see Enclosure B.6) to derive a relation between low-energy parameters of the kaon-nucleon scattering amplitude and s- and p-wave scattering lengths and to discuss various symmetry-breaking schemes.

Most recently we have written a comprehensive review (see Enclosure E.5) of chiral symmetry breaking and meson-nucleon sigma commutators, including π-N and K-N information. Here we discuss chiral symmetries, how they are broken, "experimental" estimates of σ-terms, and the connection between broken scale invariance and chiral symmetry breaking. (Reya).

C. $\pi\pi$ and $K\pi$ Phase Shifts and the Pion Exchange Mechanism

The problem of determining $\pi\pi$ and $K\pi$ phase shifts from pion production data in πN and KN collisions has been under intensive investigation at FSU and elsewhere.[1,2,3] Obtaining accurate solutions which are stable against experimental errors has always been at the heart of the problem. In addition, understanding the dominant pion exchange mechanism and parameterizing all of the experimental information available in a consistent and economical fashion is of paramount importance. In the work of Williams and others,[4-8] many of the conceptual obstacles have been overcome, and new analysis techniques have been formulated in a calculational framework incorporating absorption model considerations. The goal of obtaining accurate, stable and unique $\pi\pi$ and $K\pi$ phase shifts in the mass range 500-1000 MeV/c^2 is within reach. Toward this goal, the recent SLAC data from the 15 GeV/c (π^-p) counter experiment[9] verified convincingly the rich structure predicted by the absorption model in the near forward direction. In the application by the SLAC group[10] of an absorption model analysis formulated by Williams at FSU,[4] the fits were quantitatively good, with reasonable and interesting values for the parameters being obtained.

More recently with overwhelming statistics the CERN-Munich Collaboration counter experiment on the same reaction at 17.2 GeV/c[11] has demonstrated that the predictions of the FSU model[4] are quite accurate in the near forward direction. Some of the quantitative features of the model were included in the analysis for $\pi\pi$ phase shifts.[11]

The work at FSU has been instrumental in focusing more attention on the structure of helicity amplitudes. Indeed, the Tallahassee Conference on π-π Scattering[1] stressed "amplitude analysis" at least as much as the determination of π-π ($K\pi$) phase shifts, as of course the two are inextricably linked. The whole subject of π-π scattering is moving into this most interesting realm, through the analysis of recent experiments with huge statistics.[11,12] Details of the production amplitudes are seen to affect the qualitative aspects of the π-π phase shift determinations, leading naturally to controversies and paradoxes, the resolution of which will be exciting as well as representing real progress.

One controversy is on the question of "phase coherence" of the production amplitudes, a quality common to all simple pion exchange mechanisms even with absorption of the lowest partial waves. The amplitude analysis of Estabrooks and Martin[11,13] yields two solutions, one of which is very nearly "phase coherent", the other indicating interference effects most naturally attributed to the presence of A_2 exchange even at very small $t(-t < \mu_\pi^2)$. However, the best solution is the phase coherent one, and the resulting extrapolation to the pion pole yeilds better π-π phase shifts. The only disconcerting thing about this result is that analysis of n-p charge exchange data indicates A_2 exchange presence and phase incoherence at very small t.

Another interesting result of the analyses of Estabrooks and Martin[11] and Wagner and Ochs[14] concerns production of high mass dipion states. Here the FSU model[4] first appears to break down. This indicates trouble for all absorption models. A possible explanation is to allow considerable A_2 exchange for lower dipion mass which contributes progressively less with increasing dipion mass. Such an effect was predicted by Hoyer, Roberts and Ray.[15] Whether our treatment of pion exchange is correct for the entire dipion mass range is then still an open question.

Another recent development has been the systematic study of the $K\bar{K}$ threshold region, and the $K\bar{K}$ system itself, made possibly by newer high statistics experiments in bubble chambers[16] and in counters.[12,17] This has lead to the establishment of a new $\pi\pi$ resonance, the S*, the analysis of which required the use of coupled-channel unitarity and analyticity near the $K\bar{K}$ threshold. There remains some small doubt as to the exact position of this narrow resonance and its interpretation as a virtual bound state or antibound state. Its discovery has clearly made $\pi\pi$ scattering much richer, as it becomes possible to study inelastic effects with spin-zero particles.[18,19] (See enclosure B.18). Finally, there has been some work on the $\pi\pi$ total cross section,[20] and some promising methods have been advanced to accurately measure it. The most promising appears to be inclusive reactions like $\pi^+ p \to \Delta^{++}$+ anything where the Δ^{++} decay can be used as an analyser for the π-exchange part so that the extrapolation to the pion pole would yield clearly $\pi\pi \to$ anything, i.e. the $\pi\pi$ total cross section.[18,21] (See Enclosure B.11).

The FSU model referred to above[4] goes under various aliases, to name a few: "The OPE-δ model", "The OPEK model", "The Poor Man's Absorption Model", or "Williams' model". The model has been applied to several quite different reactions mediated by pion exchange;[23] it has been compared[23,24] to the gauge invariant Electric Born model for pion photoproduction and to the vector dominance model of Cho and Sakurai;[25] it has been studied and tested[26] in the formalism of Froggatt and Morgan; finally, it has been "Reggeized"[27]--all with rather good, interesting and successful results.

In addition, the method has been used to scrutinize analysis methods in several reactions. For example, in the reaction $\pi^+ + p \to \pi^+ + \pi^- + \Delta^{++}$, data have been handled without recourse to absorption model calculations.[16] We have shown that in some cases, in regions of special interest, the "non-absorptive" methods can be very poor.

Through the use of this model it may be possible to unify the descriptions of all pion-exchange-dominated reactions at high energy, including details of charged pion photoproduction and np charge exchange reactions,[27] which have been particularly resistent to more standard descriptions. (Williams)

D. <u>Analysis of $\Lambda\pi\pi$ and $\Sigma\pi\pi$ Final States</u>

Resonance formation K^-n interactions with subsequent decay to the three-body states $\Lambda\pi^-\pi^0$ and $\Sigma\pi\pi$ has been analyzed at FSU[28] using the three-body formalism of Deler and Valadas[29] and of Namyslowski et al.[30] This work is directed at studying Y* resonances, their quantum numbers and decay modes in the center of mass energy range 1500 to 1700 MeV. In addition, some information on non-resonant partial wave amplitudes is obtained. It is encouraging that some useful information apparently can be obtained from the three-body states. Theoretical participation has been directed toward refining this kind of analysis to the point of obtaining definitive results. Recently, Williams has been directly involved in the analysis. In particular, with student C. David Capps, an examination of the work of Namyslowski, et al. was undertaken which yielded what we feel is a significant improvement in the formulation in terms of managability, accurateness, and speed and ease of computation.[31] We have completed[31] a theoretical study of the reaction $K^-+n \rightarrow \Sigma^++\pi^-+\pi^-$ in an isobar model, with emphasis on features of the $\Sigma\pi$ mass and angular distributions for various isobars and sequential decays through various resonant $(\Sigma\pi)$ intermediate states. We also looked for effects of symmetrization due to identical pions and effects of angular momentum barriers for the resonant intermediate states. Work is nearing completion on the application of the isobar model thus formulated to the FSU data for the $\Sigma^+\pi^-\pi^-$ final state,[32] and also for the $\Lambda\pi^-\pi^0$ final state.[33] See enclosure A.1.g and B.1 (Williams, Capps).

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ENCLOSURES TO PROGRESS REPORT

For Period November 1, 1972 to October 31, 1973

A. Abstracts of Papers Presented at the American Physical Society

1. New York Meeting, January 1973; Bull. Am. Phys. Soc. Vol. 17, No. 1.

   a. "Chiral Symmetry Breaking, PCAC and the Sigma Commutator in the Kaon Nucleon System" by Reya.

   b. "Absorption Model Analysis of Single Pion Production" by Kimel and Reya.

   c. "The Reaction $\pi^+ d \to (m\pi)^+ d$ for m=3 to 8 at 15 GeV" by Horne, S. Hagopian, V. Hagopian, Pewitt, Wind and Bensinger.

   d. "Resonance Production from the Reactions $\pi^+ d \to (m\pi)^0 pp_s$ for m=2 to 8 at 15 GeV" by Bensinger, S. Hagopian, V. Hagopian, Horne, Pewitt and Wind.

   e. "A Self-Consistency Calculation of the Charge Distribution and Potential in a Migmacell" by Galayda, Robinson and Colleraine.

   f. "Experiments with Migmacell" by Maglich, Colleraine, Chieng, Galayda, Gore, Mazarakis, Miller, Robinson and Zagarino.

   g. "Partial Wave Isobar Model Analysis of $K^- n \to \Sigma^+ \pi^- \pi^-$ Near Center of Mass Energy 1690 MeV" by Capps, Harrison, Madden, Chandler, Albright and Williams.

2. Washington Meeting, April 1973; Bull. Am. Phys. Soc. Vol. 17, No. 4.

   a. "Observation of a $\Sigma(1620)$ in $\Lambda^0 \pi^-$, $\Lambda^0 \pi^- \pi^0$ and $\Sigma^0 \pi^0$ Final States in Low Energy $K^- d$ Reactions" by Morris, Albright, Colleraine and Kimel.

   b. "Experiments with a Migmacell: I. Transmission, Injection and Orbits" by Colleraine, Galayda, Leese, Maglich, Mazarakis, Miller, Zagarino, Mueller and Rago.

   c. "Experiments with a Migmacell: II. Detection of Fusion Products Produced at Migma Focus" by Maglich, Mazarakis, Zagarino, Galayda, Colleraine, Leese, Sannes, Alspector, Rago and Mueller.

d. "A Human Intervention Method to Improve the HPD Measurement Efficiency of the π^+d Interactions at 15 GeV/c" by Pewitt, S. Hagopian, V. Hagopian, Horne, Wind and Bensinger.

3. Berkeley Meeting, August 1973

a. "Measurement of N* Production in p+p → p+N* between 9 and 300 GeV/c" by Abe, Alspector, Bomberowitz, Cohen, Colleraine, DeLillo, Harrison, Maglich, Mueller, Robinson and Sannes.

B. Papers Published During the Report Period

1. "Isobar Models, Analysis and Symmetrization Effects in Meson + Baryon → Meson + Meson + Baryon" by Capps, Madden and Williams, Phys. Rev. D 7, 146 (1973).

2. "A Study of Absorptive Corrections in the Reaction $\pi^-p \rightarrow \pi^-\pi^+n$" by Kimel and Reya, Nucl. Phys. B47, 589 (1972).

3. "A_2 Exchange in the Reaction $\pi^-p \rightarrow \pi^-\pi^+n$ at 17.2 GeV/c" by Kimel and Reya, Nucl. Phys. B58, 513 (1973).

4. "Absorptive Effects in the Reactions $K^-p \rightarrow K^-\pi^+n$ and $K^+n \rightarrow K^+\pi^-p$" by Kimel and Reya, Nucl. Phys. B48, 573 (1972).

5. "Absorption Model Amplitude Analysis for the Reaction $\pi^-p \rightarrow \pi^-\pi^+n$ at 17.2 GeV/c" by Kimel and Reya, Phys. Letters 42B, 249 (1972).

6. "Chiral Symmetry Breaking Partial Conservation of Axial-Vector Currents and the σ Commutator in the Kaon-Nucleon System" by Reya, Phys. Rev. D 7, 3472 (1973).

7. "Nonvanishing Cross Section for the Reaction $\pi+N \rightarrow (\pi+\pi)+N$ at $t=0$" by S. Hagopian, V. Hagopian, Kimel, Pewitt and Selove, Phys. Rev. D 7, 1271 (1973).

8. "Asymmetry Properties of Longitudinal-Momentum Distributions for the Reaction $\pi^+p \rightarrow p8\pi$ at 11 GeV/c" by Yost, Morris, Albright and Lannutti, Phys. Rev. D 6, 3051 (1972).

9. "K^-d Elastic Scattering at 727 MeV/c" by Wieckowicz, Albright and Lannutti, Nucl. Phys. B61, 274 (1973).

10. "Structure in the Momentum Transfer Distribution of $\pi^-+p \rightarrow \rho+N$ at 2.3 GeV/c" by S. Hagopian, V. Hagopian and Selove, AIP Conf. Proc. No. 13, π-π Scattering - 1973, p. 354.

11. "π-π Coupled Channels" by Williams, AIP Conf. Proc. No. 13, π-π Scattering - 1973, p. 135.

12. "A_2-Exchange and Polarization Effects in the Analysis of $\pi\pi$ Scattering," by Kimel and Reya, AIP Conf. Proc. No. 13, π-π Scattering - 1973, p. 274.

13. "Quantization of the Spin-3/2 Field in the Presence of Interactions" by Kimel and Nath, Phys. Rev. D 6, 2133 (1972).

14. "Polarization Effects and Analysis in Meson + Nucleon → Meson + Meson + Nucleon" by Kimel and Reya, Phys. Rev. D 8, 1519 (1973).

15. "Low-Energy Kaon Nucleon Scattering and the Magnitude of the Sigma Commutator" by Reya, Phys. Letters 43B, 213 (1973).

16. "Turning Angles of Charged Particles Tracks in Large Bubble Chambers" by Knop, Rev. Sci. I. 44, 50 (1973).

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18. "Analysis of the Anomaly in the $\pi^+\pi^-$ System Near the $K\bar{K}$ Threshold" by Williams, Phys. Rev. D 6, 3178 (1972).

19. "Long Range Forces and Broken Symmetries" by Dirac, Proc. R. Soc. Lond. A 333, 403 (1973).

20. "Effects of N* Production on Nucleon-Nucleus Scattering" by M. Ikeda, Phys. Rev. C 6, 1608 (1972).

C. Book Published

1. AIP Conference Proceedings, No. 13, π-π Scattering - 1973 (Tallahassee Conference), editors P. K. Williams and V. Hagopian, American Institute of Physics, New York, 1973.

D. Ph.D. Dissertations Completed

1. "Resonance Structure in $K^-N \rightarrow Y\pi$ Reactions in the Center-of-Mass Energy Range 1550-1650 MeV" by W. A. Morris, June 1973.

2. "K^-d and K^-np Reactions at 727 MeV/c" by R. P. Wieckowicz, June 1973.

E. Papers Submitted for Publication

1. "Equivalence of Yang-Feldman and Action Principle Quantization in Pathological Field Theories" by Kimel, Gluch and Hays, submitted to Phys. Rev. Removed

2. "Study of the Nonimpulse Events in the Reactions $K^-d \rightarrow \Sigma^{\pm}\pi^{\mp}\pi^-p$ at 670-835 MeV/c" by Albright, submitted to Phys. Rev. Removed

3. "Monte Carlo Generation of Two-Body Resonant States" by Knop, submitted to Rev. Sci. I. Removed

4. "A Note on Hypercube Partitions" by Knop, accepted by J. Comb. Th. Removed

5. "Chiral Symmetry Breaking and Meson-Nucleon Sigma Commutators: A Review" by Reya, submitted to Rev. Mod. Phys. Removed

6. "Cosmological Models and the Large Number Hypothesis" by P. A. M. Dirac, submitted to Proc. R. Soc. London.

7. "Evolutionary Cosmology" by P. A. M. Dirac, to be published by the Pontifical Academy Journal Comentarii.

F. Comments on ΔΔ Component in the Deuteron

1. Comment by Maurice Goldhaber.

2. Comment by D. Allan Bromley.

G. Letters of Intent

1. MPS experiment at BNL.