MASTER

HIGH ENERGY PHYSICS

TUFTS UNIVERSITY

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High Energy Physics At Tufts University

Whereas the period up to 1969 was one of rapid expansion, the period 1969-1973 has been one of consolidation and adjustment to meet new conditions. With reduced budgets, a deliberately decreased graduate program, and the end of AEC support for the theorists in 1971, we have had to find new ways of operating. Through increased collaboration, thrift, and harder work the accomplishments of the high energy group in the last five years are greater than in the previous five years.

Despite the fiscal problems which Tufts along with most other Universities is experiencing it has continued support of the High Energy Physics program beyond its contractual agreement with the Atomic Energy Commission. By acquiring a Decsystem 10 computer in January 1973, Tufts is assisting the work of the program and will do so increasingly in the future. With direct access to the computer from the laboratory there is no longer the need to use remote computers such as those which have been used at New York University, Brookhaven National Laboratories, and the Smithsonian Astrophysical Observatory. The great gain in convenience, and hence time, and the probable saving in costs will materially assist the program. Tufts has continued financial support of overseas and local travel expenses, and support not readily measured in dollars. For example, Tufts has permitted the Physics Department to make its own arrangements to have faculty members at SLAC for periods as long as a full term without requiring these faculty members to take leaves of absence. As another example, when support for the Theory Group ended in December 1971 Tufts could have terminated the contract of an Assistant Professor, part of whose salary was being paid by contract funds. It did not, but instead assumed the additional financial burden.

The joint support of the Atomic Energy Commission and Tufts University have enabled high energy physics to flourish at Tufts as an enterprise in research and education in difficult times.

The most recent history and present status of high energy physics at Tufts are described below under the headings of groups presently active or active in the period 1969-73.

Tufts Bubble Chamber Group
Summary of Research
1969-1973

Personnel: The personnel of the Bubble Chamber Group presently consists of: Prof. J. Schneps, Asst. Prof. Canter (1970-), Asst. Prof. Wolsky, Dr. Mann (1972-), Messrs. Tompkins, Katsoufis and Gelfand.

Past members of the group are: Asst. Prof. Bartley (-1969; now at University College London, England); Asst. Prof. Dowd (-1970; now at Department of Pollution Standards, State of Connecticut, Hartford, Connecticut); Dr. Govan (1976-1972; now at Sevenoaks School, London, England); Mr. Chu (Ph.D. 1971; now at State University of New York, Plattsburgh, N.Y.); Mr. Sanders (Ph.D. 1972; now at Rockefeller Foundation, New York, N.Y.); Mr. Brenner (Ph.D. 1972; now at Tufts New England Medical Center, Boston Mass); Ms. Patel (M.S. 1969) and Mr. Armenian (M.S. 1972)

Prof. Schneps is currently spending his sabbatical year at University College London, England.

During the last five years the Tufts Bubble Chamber Group has concentrated its efforts on the analyses of film from four bubble chamber exposures (1. BNL 31" K⁻p; 2. BNL 31" K⁻d; 3. BNL 30" K⁻d; and 4. Rutherford Lab. K⁻- Heavy Liquid). We are currently preparing for a new K⁺-hydrogen exposure in the ANL 12' hydrogen bubble chamber. In addition, we are planning to use new facilities becoming available to the high energy community at the National Accelerator Laboratory, and Brookhaven National Laboratory. Proposals have been submitted for the BNL 7' bubble chamber with a track sensitive target and the NAL 15' chamber. We are considering a proposal for the NAL 30" bubble chamber with a neon fill. We have improved our data reduction capabilities by placing our conventional measuring machines on-line to a PDP-8 computer and increasing our processing efficiency. An automatic measuring machine is under development. Our accomplishments and future plans are described in detail in the following sections.

1. B.N.L. 31" K^-p Bubble Chamber Exposure

a) Events with Two Signs of Strangeness

The primary purpose of this exposure was to perform an accurate, high statistics study of strangeness - 2 baryon resonances. The Ξ^* situation has long been unsettled. This is because Ξ^* 's can only be observed in production experiments as part of a final state, and they are produced with small cross sections ($< 50 \mu\text{b}$).

Before the start of this experiment there were three reported signals below 2 GeV, at 1530, 1815, and 1930 MeV. In addition, there was an unconfirmed enhancement at 1705 MeV. The Ξ (1530) was the only well-established resonance in this group. It can only decay strongly into $\Xi \pi$. However, its measured width disagreed with the SU_3 prediction. The resonance parameters and decay modes of the Ξ (1815) and Ξ (1930) were poorly known.

We have completed an experiment to do a careful study of the Ξ^* spectrum below 2 GeV. One million pictures were obtained from an exposure (completed in 1968) of the Brookhaven National Laboratory 31" hydrogen bubble chamber to an incident K^- beam of momentum 2.9 GeV/c. The large scale of this experiment required that the film be analyzed at four institutions, Brandeis University, University of Maryland, Syracuse University, and Tufts University.

The first phase of this experiment was a study of the final states with two or more visible signs of strangeness. The results have been published. The observed signals are summarized in Table I.

Above 1600 MeV the situation is more complex than had been reported by previous experiments. In our data no peak in any given channel has outstanding significance by itself. In addition it is not clear which of the peaks should be considered as different decay modes of the same particle. For this reason, branching ratios are not quoted. Indeed, we expect to find several Ξ^* 's below 2 GeV. SU_3 symmetry predicts that for each N^* or Δ there is a Ξ^* . This is summarized by Harari in his rapporteur's talk at the Vienna Conference (1).

TABLE ISUMMARY OF OBSERVED RESONANCES

<u>Mass (MeV)</u>	<u>Observed Width (MeV)</u>	<u>Decay Mode</u>	<u>Channel</u>	<u>Fraction %</u>
1531 $\pm$ 1	13 $\pm$ 2	$\Xi^- \pi^+$	$\Xi^- \pi^+ K^0$	21.9 $\pm$ 1.4
<u>1530</u>	28 $\pm$ 22	$\Xi^- \pi^0$	$\Xi^- \pi^0 K^+$	12.0 $\pm$ 3.0
<u>1531</u>	13	$\Xi^0 \pi^-$	$\Xi^0 \pi^- K^+$	16.4 $\pm$ 2.8
1635 $\pm$ 10	57 $\pm$ 18	$\Xi^- \pi^+$	$\Xi^- \pi^+ K^0$	6.8 $\pm$ 1.4
<u>1635</u>	<u>57</u>	$\Xi^0 \pi^-$	$\Xi^0 \pi^- K^+$	<8.1 (95% C.L.)
1795 $\pm$ 10	99 $\pm$ 31	$\Xi^- \pi^+$	$\Xi^- \pi^+ K^0$	10.5 $\pm$ 2.4
<u>1795</u>	99	$\Xi^0 \pi^-$	$\Xi^0 \pi^- K^+$	17.2 $\pm$ 6.4
1820 $\pm$ 12	82 $\pm$ 42	$\Xi(1530) \pi$	$\Xi \pi \pi K$	18.1 $\pm$ 3.5
1827 $\pm$ 8	38 $\pm$ 16	ΛK^-	$\Lambda K^- K^+$	6 $\pm$ 2
1854 $\pm$ 12	56 $\pm$ 14	$\Sigma^- \bar{K}^0$	$\Sigma^- \bar{K}^0 K^+$	34.0 $\pm$ 9.5
1871 $\pm$ 11	58 $\pm$ 39	$\Lambda \bar{K}^0 + \Lambda K^0$	$\Lambda \bar{K}^0 K^0$	13.4 $\pm$ 4.6
<u>1954</u>	<u>129</u>	$\Xi^0 \pi^-$	$\Xi^0 \pi^- K^+$	18.7 $\pm$ 6.8
1954 $\pm$ 9	129 $\pm$ 3	$\Xi^- \pi^+$	$\Xi^- \pi^+ K^0$	19.0 $\pm$ 2.9
1961 $\pm$ 8	42 $\pm$ 35	$\Xi(1530) \pi$	$\Xi \pi \pi K$	15.0 $\pm$ 3.3

Quantities underlined are treated as fixed parameters.

The main features of the data, besides the $\Xi(1530)$, are as follows: The $\Xi(1635)$, a greater than three standard deviation effect, was first seen in this experiment. Its status as a resonance is "in need of confirmation".⁽²⁾ The three-body data also shows a broad high-mass enhancement, highly suggestive of a splitting into two narrower resonances at 1800 and 1960 MeV. In the four-body data strong effects are seen in the $\Xi(1530)\pi\pi$ system. These occur at masses of 1820 and 1961 MeV. This was the first convincing evidence of a resonance in the $\Xi(1530)\pi\pi$ system. Combining the three- and four-body data establishes the $\Xi(1820)$ and $\Xi(1960)$ in our data. The $\Lambda K\bar{K}$ and $\Xi K\bar{K}$ final states are dominated by ϕ production. With the removal of the ϕ events, the $\Lambda K\bar{K}$ system shows evidence for structure at about 1860 MeV. In the $\Xi K\bar{K}$ final states only ΞK^0 shows any structure and this is in the vicinity of 1860 MeV.

For this phase of the experiment Tufts' primary responsibility was a careful study of the two charged states of the $\Xi(1530)$. We found the masses of the $\Xi^0(1530)$ and $\Xi^-(1530)$ to be 1532.3 ± 0.7 MeV and 1536.2 ± 1.6 MeV respectively, giving an electromagnetic mass difference of 3.9 ± 1.8 MeV. We obtained widths of 11.0 ± 1.7 MeV for the $\Xi^0(1530)$ and 16.2 ± 4.6 MeV for the $\Xi^-(1530)$. The former was in disagreement with the previously accepted value of 7.3 ± 1.7 MeV but in agreement with the predictions of SU_3 , while the latter was the first reported measurement.

We attempted to measure the spin and parity of various Ξ^* 's using the method of Byers and Fenster. There was no spin parity discrimination at any mass value due mainly to the absence of sufficient polarization. The method of Button-Shafer⁽³⁾ was applied to a spin parity analysis of $\Xi(1820)$ and $\Xi(1960)$ in the $\Xi(1530)\pi\pi$ system. In both cases the series $3/2^-$, $5/2^+$, was slightly preferred. For $\Xi(1960)$ $1/2^-$ and $1/2^+$ were also allowed.

The reaction $K^- + p \rightarrow \Xi^- + \text{anything}$ was studied using both our data and those of the BNL-Syracuse collaboration (3.9, 4.6 and 5.0 GeV/c incident momentum). This is potentially very different from the class of inclusive reactions that have been analyzed previously. We find that $\langle P_z^2 \rangle$ depends on both the center of mass energy and on χ , the longitudinal component of the Ξ^- momentum in the center of mass system. The shape of $d\sigma/dx$ is independent of center of mass energy. More interesting conclusions would require data at much higher incident momentum. These results were presented to the XVI International Conference on High Energy Physics in Chicago.

b) Two Prong plus Vee Topology

The second phase of our experiment (in collaboration with Maryland and Syracuse) was a study of the topology 2 prongs + vee. The primary objective was an extension of the above study of strangeness - 2 baryon resonances. In particular, we were able to study the final states $\Xi^0 \pi^- K^+$, $\Lambda K^- K^+$ and $\Xi^0 K^- K^+$ which do not have two visible signs of strangeness. These data were incorporated in our discussion of the Ξ^{*} 's in Part a.

This topology allowed us to study η' production in the reaction $K^- p \rightarrow \Lambda \eta'$. We measured branching ratios of

$$\frac{\eta' \rightarrow \pi^+ \pi^- \gamma}{\eta' \rightarrow \pi^+ \pi^- \eta} = 1.11 \pm 0.18$$

$$\frac{\eta' \rightarrow p \gamma}{\eta' \rightarrow \pi^+ \pi^- \gamma} = 1.01 \pm 0.15$$

A matrix element analysis yields both 0^- and 2^- as acceptable spin parity values. Production decay angular correlations suggest that a 2^- assignment is unlikely.

In the K^0 channels we have been analyzing the final states $\bar{K}^0 \pi^- p$, $\bar{K}^0 \pi^- \pi^0 p$ and $\bar{K}^0 \pi^- \pi^+ n$. Production of $K^*(890)$ and $\Delta(1236)$ are the predominant features of these channels. The production characteristics are being studied. These reactions are also being analyzed to obtain cross sections and phase shifts for $K\pi$ scattering. Results with various combinations of vertex correction factors have been obtained. Although pion exchange accounts for less than 50% of these reactions, we are obtaining results in agreement with other workers.

Data from the three body channel, $\bar{K}^0 \pi^- p$, has been compared to the Veneziano type models of Chan, Raitio, Thomas and Tornqvist (CRTT) ⁽⁴⁾ and of Waluch, Flatte, Friedman and Sivers (WFFS) ⁽⁵⁾. The WFFS model gave better fits to the data from the reaction $K^+ p \rightarrow K^* \pi^+ p$ at 12 GeV/c. Predictions, at our energy, for the two models have been generated by Dr. D. Sivers of Argonne National Laboratory. We found that the WFFS model fit the four momentum transfer

and Jackson angle distribution better than the CRTT model. However, this was at the expense of the mass distributions which were better fitted by the CRTT model. This work was the subject of the Ph.D. thesis of J. Brenner. Tufts is currently preparing a paper summarizing all the work on the $\bar{K}^0$ channels.

The situation in the region of the $\Sigma(1660)$ appears to be very complex. There are at least two resonances, one seen mainly in formation experiments, the other seen mainly in production experiments. In addition, in the production experiments the measured branching ratios vary with momentum transfer to the proton suggesting the possibility of a third Y^* state in this region.

In the two prong vee topology the $\Sigma(1660)$ could be produced in the reactions $K^-p \rightarrow \Sigma^0 \pi^0 \pi^-$, $\Lambda \pi^0 \pi^-$, $\Lambda \pi^+ \pi^- \pi^0$ and $\bar{K}^0 p \pi^-$. Brandeis University has analyzed the topologies two prong with a kink and four prong with a kink for final states with a Σ^+ hyperon. An analysis of the combined data has been performed for the reaction $K^-p \rightarrow \Sigma^+(1660) \pi^-$. The primary decay mode of the $\Sigma(1660)$ is $\Lambda(1405) \pi^-$. We also find evidence for this resonance decaying into $\Sigma \pi$, $\Lambda \pi$ and $\Sigma(1385) \pi$. There is disagreement between various experiments on the branching ratios as has been summarized by P. Eberhard.⁽⁶⁾ We have also measured the spin parity of the $\Sigma(1660)$ to be $3/2^-$. A paper has been submitted to Nuclear Physics.

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Dissertations

The Reaction $K^- p \rightarrow \bar{K}^0 \pi^- p$ at 2.9 GeV/c with a Comparison to
Several Veneziano Type Models. J.F. Brenner (Ph.D. 1972)

2. BNL 31" Deuterium Bubble Chamber Exposure

a) Events with two signs of strangeness.

A one million picture exposure of the BNL 31" bubble chamber, filled with deuterium, to a 2.9 GeV/c K^- beam was begun in late 1970 (in collaboration with Brandeis, Maryland and Syracuse). This experiment complements our K^-p exposure by making possible the separation of the $I = 0$ and $I = 1$ Ξ^- production amplitudes. Also, the neutron target channels $Y^0 K^- K^0$ are free of the $\phi \rightarrow KK$ signal which dominates the corresponding proton target channels.

The collaboration has completed a final data summary tape containing 4,811 events with two signs of strangeness. Tufts has contributed approximately one-third of this data. We have assumed primary responsibility for the analysis of the $YK\bar{K}$ final states. This will be the subject of a Ph. D. thesis by Mr. J. Tompkins.

Analysis is near completion and preliminary results were presented to the Hyperon Conference held at Purdue University. The following conclusions have been drawn:

1. There is no significant Ξ^- resonance production, besides the Ξ^- (1530) in K^-n interactions at 2.9 GeV/c at a level of about 2 - 4 μb .
2. Ξ^- resonances below 2 GeV in mass which decay into $\Xi^- \pi^+$ have isospin 1/2 rather than 3/2.
3. There is an approximately three standard deviation Ξ^- (1635) signal in the reaction $K^-d \rightarrow \Xi^- \pi^+ K^0 n_s$.
4. Upper limits have been placed on the production of exotic ($I = 3/2$) Ξ^- resonances at 2.9 GeV/c. At the 90% confidence level and for a width less than 40 MeV, they are:

<u>Decay Mode</u>	<u>Reaction</u>	<u>Upper Limit</u> (μb)
$\Xi^- \pi^-$	$K^- n \rightarrow \Xi^- \pi^- K^+$	2.4
$\Xi^- \pi^-$	$\rightarrow \Xi^- \pi^- \pi^+ K^0$	1.7
$\Xi^- \pi^-$	$\rightarrow \Xi^- \pi^- \pi^0 K^+$	1.2
$\Xi^- (1530) \pi^-$	$\rightarrow \Xi^- \pi^- \pi^0 K^+$	1.2

We expect that the analysis of cascade resonances produced in neutron reactions to be completed by the end of the year. We will also study the proton reactions (with spectator neutrons) which are on the data summary tape. These events will be used to increase the statistics of our previous experiment in hydrogen. Comparisons will be made between cascade production from neutron and proton targets.

b) $S = -2$ Dibaryon System

The scanning rules for this experiment also pick up events where the K^- interacts with the deuteron to give final states with two Λ 's or $\Xi^- p$. These events are of interest to us since we are engaged in the study of the strangeness -2 dibaryon system in our heavy liquid film. The fact that we will fit the production reaction in deuterium will enable us to obtain a better handle on the production mechanism. At present we have studied the events with two Λ 's from our portion of the film (about 50 events) and find no evidence of structure in the $\Lambda\Lambda$ invariant mass spectrum. We will soon obtain the data from the rest of the collaboration and will also analyze the $\Xi^- p$ spectrum.

c) $K^- n \rightarrow \xi^- \pi^- \pi^+ (\pi^0)$ (In collaboration with Brandeis)

We are also studying the $\xi^- \pi^- \pi^+ (\pi^0)$ final states in the $K^- d$ film. By looking at the $\xi^- \pi^- \pi^+ (\pi^0)$ system we can search for the existence of an exotic baryon state with $I = 2$. Although no clear evidence for exotic baryons or mesons has been found, there has been some evidence for the existence of exotic amplitudes (exchange of exotic states). This suggests that the search for exotic states be pressed in many different channels. We have potentially available to us in this final state a data sample considerably in excess of the present world total. Our large statistics will also enable us to examine more closely non-exotic meson and hyperon resonances in the 1 - 2 GeV range; in particular, we hope to be able to shed some light on the Y^* 's in the 1700 MeV region.

The 126 rolls at Tufts have been scanned twice, two passes of measuring have been made, and the data processed through TVGP and SQUAW. Before second measurements were made, first measurement

SQUAW tapes were examined by a computer program to eliminate as remeasurement candidates all measuring or processing failures which did not meet certain geometric or kinematic requirements.

Tufts has written programs to write and read a data summary tape and these are now being tested. We have edited a sample of the film on the scan table. We expect to be able to use the results of this editing to devise techniques to avoid a full editing of the entire data sample. If the results warrant it, we will be able to double our present statistics by borrowing the remaining film from Maryland and Syracuse. This work will be the subject of a Ph.D. dissertation of Mr. E. Katsoufis.

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3. BNL 30" K⁻n Bubble Chamber Exposure

Two experiments have reported an enhancement in the cross section for the reaction $K^-n \rightarrow \Sigma^- \eta$ near threshold. In the Wisconsin experiment (1) the center of mass angular distribution was found to be isotropic, suggesting that only an S-wave effect is present. However the CERN-Heidelberg-Saclay (2) angular distribution suggested the presence of a D₅ wave. It was possible to interpret the results either in terms of an S-wave scattering length or as a resonance. If it is a resonance it may be the $\Sigma(1750)$, known to decay into $\bar{K} N$ and $\Lambda \bar{\pi}$, and may belong to an octet with the well known $N \eta$ and $\Lambda \eta$ resonances.

We obtained, with Brandeis University, 90,000 pictures from the 30" bubble chamber at Brookhaven National Laboratory; 60,000 at 970 MeV/c and 30,000 at 980 MeV/c. The exposure was completed in 1969. The Fermi momentum of the neutron in deuterium allows us to cover the energy region surrounding threshold for the reaction $K^-n \rightarrow \Sigma^- \eta$.

In our data a fit to the angular distribution indicated a possible contribution from the second Legendre polynomial at about two standard deviations. The CERN-Heidelberg-Saclay data also showed a contribution from this term at the same level of significance. The Wisconsin data was more consistent with isotropy. Combining the data from all three experiments yields a distribution with no significant anisotropy. This implies that a $J = 1/2$ amplitude dominates production. However, a d-wave contribution cannot be ruled out. Assuming S-wave scattering a fit to a zero effective range approximation yields a scattering length of $(0.92 \pm 0.12) \pm i(0.04 \pm 0.28)f$. A fit to an S-wave resonance gives a mass of 1785 ± 12 MeV and a width of 89 ± 33 MeV.

This work was the subject of the thesis of Mr. R. Chu and has been accepted for publication.

References

1. D. Cline and M. Olsson. Phys. Letters 25B, 41 (1967)
2. CERN-Heidelberg-Saclay Collaboration. Results presented at the Berkeley International Conference on Elementary Particles (1966) and at the Heidelberg International Conference on Elementary Particles (1967)

Publications

$K^-n \rightarrow \Sigma^- \eta$ near Threshold. R.Y.L. Chu, J. Bartley, R.M. Dowd, J. Schneps, J. Tompkins and G. Wolsky (with authors from Brandeis) to be published in Il Nuovo Cimento.

Dissertations

$K^-n \rightarrow \Sigma^- \eta$ near Threshold. R.Y.L. Chu (Ph.D. 1971)

Determination of the Composition of a Mixed Particle Beam.
G. Patel (M.S. 1969)

4. Rutherford Laboratory Heavy Liquid Bubble Chamber Exposure

A 640,000 picture exposure of the Rutherford heavy liquid bubble chamber to a 2.1 GeV/c K^- beam was taken in 1969 in collaboration with University College London, University of Brussels, and CERN. The Tufts share was 130,000 pictures. Work on the proposed experiments using this film was completed in 1972. Nearly all of the results summarized below have been published.

a) Hyperon Lifetimes and Decay Parameters.

The major goal of the exposure was to measure the lifetime and decay parameter α of the neutral cascade decay $\Xi^0 \rightarrow \Lambda \pi^0$. The difficulties in studying this decay are the low cross sections for Ξ^0 production and the fact that the decay proceeds through a completely neutral vertex. We sought to overcome these by using a large exposure in a heavy liquid chamber in which an appreciable fraction, about 55%, of the γ 's from the final-state π^0 convert to electron pairs. The position of the decay vertex, which is required to measure the lifetime, is determined by the intersection of the line of flight of a γ with that of the final-state Λ .

The entire film sample was double-scanned for K^- interactions yielding Ξ^0 candidates. After kinematic fitting and the application of preliminary cuts to eliminate backgrounds we were left with 232 events, 62 of which had two γ -rays and 170 of which had only one. A final series of cuts were made to further reduce the background and to obtain a geometrically and kinematically well-defined sample. The final sample used in the lifetime determination consisted of 157 events. After applying corrections for experimental biases, background contamination and attenuation by interactions in the liquid, the final result

$$\tau_{\Xi^0} = (2.90 \pm_{0.27}^{0.32}) \times 10^{-10} \text{ sec. was obtained.}$$

In the same scan we also obtained 831 Ξ^0 decays and after appropriate cuts analyzed the lifetime for the remaining 680. The result obtained was

$$\tau_{\Xi^0} = (1.73 \pm_{0.07}^{0.08}) \times 10^{-10} \text{ sec.}$$

We also determined the α parameters for the Ξ^0 and Ξ^- decays. The results obtained are $\alpha_{\Xi^0} = -0.84 \pm 0.27$ and $\alpha_{\Xi^-} = -0.42 \pm 0.11$.

The error on the Ξ^0 value is large, and the ratio α_0 to α_- is consistent with the value 1.00, expected if the $\Delta I = 1/2$ rule holds. For the lifetimes the ratio τ_0/τ_- is also consistent with the $\Delta I = 1/2$ value of 2.00.

This analysis constituted a doctoral thesis for Mr. A.J. Sanders of Tufts University.

b) Hyperon Masses.

The Ξ events were separately analyzed to determine the hyperon masses since the Ξ mass is the least well known of the stable baryons.

The final results obtained were (in MeV):

$$\begin{aligned} M_{\Xi^-} &= 1321.12 \pm 0.41 \\ M_{\Xi^0} &= 1315.2 \pm 0.9 \\ M_{\Xi^-} - M_{\Xi^0} &= 5.9 \pm 1.0 \end{aligned}$$

In comparison we give the previous Particle Data Group Values:

$$\begin{aligned} M_{\Xi^-} &= 1321.30 \pm 0.15 \\ M_{\Xi^0} &= 1314.7 \pm 0.7 \\ M_{\Xi^-} - M_{\Xi^0} &= 6.6 \pm 0.7 \end{aligned}$$

Our results are in good agreement with the Coleman-Glashow equation:

$$(M_{\Xi^-} - M_{\Xi^0}) + (M_{\Sigma^+} - M_{\Sigma^-}) + (M_n - M_p) = 0$$

c) $Y^* \rightarrow \Lambda \gamma$ Experiment

A Russian group presented evidence for an enhancement in the invariant mass spectrum which was interpreted as the decay of a resonance $Y_0^*(1327) \rightarrow \Lambda \gamma$. We studied events consistent with the reaction $K^- p \rightarrow \bar{\pi}^+ \pi^- \Lambda + \gamma (\gamma \geq 1)$ in order to investigate the possibility of a $\Lambda \gamma$ enhancement. Some 1300 events were used in the analysis, and we found no evidence for a $\Lambda \gamma$ resonance. With 90% confidence we determined the upper limit of the cross section for $K^- p \rightarrow Y^*(1327) \pi^+ \pi^- (\pi \pi^0)$ to be 98 microbarns.

d) $\Lambda\Lambda$ Experiment

We have studied the $S = -2$ dibaryon $\Lambda\Lambda$ system. The data came from a scan for final states with two Λ 's and a $K^0, +$ signature. The number of $\Lambda\Lambda$ K events obtained by the collaboration was 316; use was also made of 77 events - picked up incidentally in scanning - which had no K signature. After cuts were applied which removed events in which one of the lambdas may have scattered, the $\Lambda\Lambda$ invariant mass spectrum exhibited two clear peaks, one at 2270 MeV and the other at 2370 MeV.

Calculations were made which indicate that the dominant mechanism for producing $\Lambda\Lambda$ pairs from heavy nuclei is a two-step process:

In the context of such reaction sequences, our peak at 2270 is interpretable as a threshold effect since its mass is very near the $\Xi + N$ threshold. For the peak at 2370 MeV, however, the most straightforward explanation is that it is a resonance produced in $\Xi + N$ collisions which subsequently decays via two lambdas. Although enhancements exist (or have been claimed) in other dibaryon systems such as NN and ΛN , this is the first report of a possible resonance in a $S = -2$ di-baryon system which is not interpretable as a threshold effect.

Mr. H.K. Armenian of Tufts University analyzed these events for his Master's thesis.

e) $S = -2$ Dibaryons

After the above results were presented in Physics Letters, the collaboration received a communication from experimenters at Berkeley who were studying events containing two lambdas produced from K^- interactions with a thin platinum plate mounted inside a bubble chamber. Their preliminary $\Lambda\Lambda$ mass distribution also contained two peaks, and was nearly identical to the collaboration's published distribution.

Thus, in early 1973, it was strongly agreed among the collaborators that our enhancement needed a more extensive investigation. A new scan was undertaken for all events containing two candidate lambdas, including those without a K signature. We expect the new scanning to provide a three-fold increase in the $\Lambda\Lambda$ event sample.

It was also decided that a Ξ^-p (fast) mass spectrum should be obtained since the relative rates of a dibaryon decaying into Ξ^-p versus $\Lambda\Lambda$ could indicate its SU_3 assignment. For example, for S-wave decays one expects

SU_3 - Multiplet	$\Gamma(\Lambda\Lambda) / \Gamma(\Xi^-p)$
$\{27\}$	5.2
$\{8\}$	2.3
$\{1\}$	0.58

The new scan for $\Lambda\Lambda$ was begun in March; a complete double-scan of the Tufts film will be finished in November. About one-third of the new $\Lambda\Lambda$ candidates have been measured and processed on the University's PDP-10 computer. Complete measurement of $\Lambda\Lambda$ and Ξ^-p candidates will require about 10 weeks from the finish of scanning. Prof. J. Schneps is also participating in this work at University College London, while he is on leave.

Publications

A Search for the Radiative Decay $Y_0(1327) \rightarrow \Lambda \gamma$. R.M. Dowd, M. Govan, A.J. Sanders, J. Schneps and G. Wolsky (with authors from Brussels, CERN and University College London) Phys. Letters 33B, 441(1970)

A Measurement of the Ξ Hyperon Lifetimes and α Parameters. R.M. Dowd, M. Govan, A. Sanders, J. Schneps and G. Wolsky (with authors from Brussels, CERN and University College London) Nucl. Phys. B47, 333(1972)

An Enhancement in the $\Lambda\Lambda$ Invariant Mass Spectra. H.K. Armenian, M. Govan, J. Schneps and G. Wolsky (with authors from Brussels, CERN, and University College London) Phys. Letters 39B, 671(1972)

The Masses of the Ξ Hyperons. R.M. Dowd, M. Govan, A. Sanders, J. Schneps and G. Wolsky (with authors from Brussels, CERN, and University College London) Phys. Letters 42B, 372 (1972)

Dissertations

Determination of the Mean lives of the Cascade Hyperons.
A.J. Sanders (Ph.D. 1972)

Invariant Mass of the $\Lambda\Lambda$ System from an Exposure of Propane-Freon to 2.1 GeV/c K^- Beam. H.K Armenian (M.S. 1972)

5. ANL 12' K^+p Exposure

We have joined with the University of Massachusetts at Amherst * bubble chamber group in collaboration on an experiment to study 6.5 GeV/c K^+ interactions in the 12-foot bubble chamber. We have been approved for 250,000 pictures. One physicist from each group will participate in tuning of the R.F. separated beam line to the 12-foot chamber during late September. First pictures for this experiment should be taken by the end of 1973.

Our primary goal in the K^+ hydrogen film will be to isolate the 62,000 events from the reactions $K^+p \rightarrow K^0 \pi^+ \pi^+ p$ and $K^+ \pi^- \pi^+ p$. The bubble chamber provides a large usable interaction volume (30 events/ μ b in 250,000 pictures); within this volume abundant detection of decaying K^0 's will be possible as will detection of stopping protons from primary vertices at the scanning level (open track halos). These features will enable us to perform a high statistics study of diffractive strange-meson production in the region of the Q enhancement. With regard to clarification of the Q, two features of this experiment will be intensively explored:

1. If the Q consists of two 1^+ resonances as is suggested in some other experiments by its broad, flat or split mass distribution, one expects the relative phase of the $K\rho$ and $K^*(890)\pi$ channels to vary with $K\pi\pi$ mass. "The $K^0 \pi^0 \pi^+$ channel is a better place to find the phase than the $K^+ \pi^- \pi^+$ channel. Not only does an isospin Clebsch-Gordan provide more $K\rho$, but also in $K^+ \pi^- \pi^+$ there are the $K^+ \pi^+$ ambiguities right where the bands cross and interference is maximal." (1) In the 12-foot chamber we will obtain one of the largest samples of constrained $K^0 \pi^0 \pi^+ p$ events from a single incident momentum.

2. Calculations performed at ANL by Ed Berger and Geoffrey Fox indicate that Deck-type models and resonance models for the Q differ rather dramatically in their predictions for final state proton polarization. Secondary scatters of final state protons may allow us to analyze their polarization.

This experiment will be the only sizeable K^+H_2 bubble chamber exposure at 6.5 GeV/c and will represent a 6-fold increase over exposures at 5.5 and 7.3 GeV/c. We will also be able to perform significant studies of $K-\pi$ scattering phase shifts and of anti-hyperon production.

* See Addendum

In preparation for this experiment the Tufts group has scanned, measured, and reconstructed events from a 7.2 GeV/c p-H₂ test roll from the 12-foot chamber. We have also studied reconstruction accuracy and measuring rates as functions of various choices of chamber-based and camera-based fiducials.

Footnote

1. M.G. Bowler, presented at the Bologna Conference of 1971, Edited by Dolitz and Flicheche, p.149.

6. Future Experiments

a) Study of $K_{\ell 3}$ decays in the BNL 7' Chamber with a TST.

It is expected that a low energy separated beam will be built to the Brookhaven National Laboratory seven-foot bubble chamber. When this occurs we would like to study K^+ decays with emphasis on the $K_{\ell 3}$ form factors. We would use a track sensitive target surrounded by a hydrogen-neon mixture. A one-million picture exposure would yield a significant improvement in our knowledge of these form factors. In this experiment we would be able to study both $K_{\mu 3}$ and $K_{e 3}$ decays and determine the form factors by the Dalitz plot method, polarization method and branching ratio method. The only experiment to utilize all three methods was the heavy liquid, x2 experiment (1) which had less than 10,000 events per method. We should have at least five times their data. The TST will afford the additional advantage of enabling measurement of the momenta of charged decay products in hydrogen, thereby increasing experimental sensitivity. Preliminary Monte Carlo studies have been quite encouraging.

Prof. J. Schneps was a member of the x2 collaboration and is familiar with the problems of the experiment. He is spending the current academic year at University College London, where he is working on an experiment utilizing the Rutherford Laboratory chamber with a track sensitive target.

A collaboration has been formed with the bubble chamber groups of Brookhaven National Laboratory and Case-Western Reserve University and a letter of intent was submitted to Brookhaven National Laboratory. At present, the time estimates at Brookhaven call for construction of the low energy beam at the beginning of 1976. We are delaying the writing of a formal proposal to a more appropriate date.

b) Study of Neutrino Interactions in the NAL 15-foot Deuterium Bubble Chamber.

We have submitted, together with physicists from the State University of New York at Stony Brook, a proposal to the National Accelerator Laboratory to study neutrino-deuterium interactions in the 15-foot bubble chamber. (2) Using the latest estimates of obtainable neutrino fluxes, we find that an initial 300,000 picture exposure in a focused neutrino beam from 350 GeV/c protons will complement existing proposals and enable a rich variety of measurements. At this energy and large q^2 we will be able to study "elastic" form factors, $\Delta(1236)$ production and the $|\Delta I| = 1$ selection rule, the $\Delta S = \Delta Q$ rule and strange particle associated production.

In the reaction $\nu_\mu + n \rightarrow \mu^- + p$ an accurate determination of the axial form factor will be possible. This will be an important extension to higher q^2 of the form factor fits obtained at Argonne and Brookhaven. At higher q^2 one may detect form factor behavior different from the dipole form which is adequate for the low q^2 experiments. Anomalous behavior at large E_ν and q^2 could signal the presence of second class currents such as an axial magnetic transition.

The inelastic events will allow investigation of the linear rise or turnover of the neutrino-nucleon cross section, the difference between $\sigma(\nu n)$ and $\sigma(\nu p)$, and the details of final-state hadron production such as structure functions, multiplicities, and momentum spectra.

A light-liquid bubble chamber experiment affords an excellent environment in which to undertake detailed studies of new phenomena such as neutral current processes or new weakly-interacting particles. Of highest priority will be isolation of the neutral-current component in neutrino interactions which has very recently been cited in massive-detector experiments at NAL and CERN. The large rate reported for neutrino reactions which contain no final-state muons - about 30% of the rate for charged-current reactions - implies that significant work can be done in the 15-foot chamber even if external muon identification is not available. That is, a sizeable number of events should occur in which all negative particles are identifiable as hadrons via their secondary interactions.

One of us (W.A.M.) has gained 2 years experience in the ν_μ -hydrogen and deuterium experiments with the Argonne 12-foot bubble chamber.

c) Proton-Neon Interactions in the NAL 30-inch Bubble Chamber to Distinguish Multiparticle Production Mechanisms.

Inclusive reactions from protons on nuclei have been treated in theoretical calculations using an extended formulation of Glauber multiple-scattering theory. For the primary proton-nucleon collision inside a heavy nucleus ($A > 10$) two classes of multiparticle production have been considered. The classes contain either multiperipheral

or fragmentation-type models, and they roughly define the extremes of current viewpoints about high energy collisions. The most recent calculations (3) appear to us to offer very significant predictions which a bubble chamber experiment can readily check.

In a multiperipheral process particles are produced instantly, while in a fragmentation process a primary collision yields an excited state which then propagates as a localized entity through a nucleus before decaying into many particles. It is found from calculation that multiperipheral particles can induce many more slow pions through intranuclear cascading than can excited fragments. Thus for 200 GeV/c proton interactions with neon, very different distributions in inclusive pion number versus rapidity are implied. In the fragmentation picture the rapidity distribution for π 's is expected to be rather similar to the corresponding distribution for p-hydrogen collisions. However, if multiperipheral processes dominate, a large increase in the number of low-rapidity π 's compared to the p - H₂ case is expected.

The π^- rapidity from 200 GeV/c protons on hydrogen has already been measured in the bare 30" NAL bubble chamber (4). A similar measurement using a neon fill is clearly feasible with a small number of pictures. Since multiplicity and rapidity distributions from p - neon interactions are predicted to change with incident momentum, it would be desirable to take small exposures at several different momenta. We believe that the physics to be done is not adequately covered by earlier 30" bubble chamber proposals (which expressed interest in π^0 physics) and hence we will submit an additional proposal.

References

1. X2 Collaboration. Phys. Rev. D3, 10 (1971)
2. NAL Proposal No. 227
3. P.M. Fishbane and J.S. Trefil. Phys. Rev. Lett. 31, 734 (1973)
4. Y. Cho et al. Phys. Rev. Lett. 31, 413 (1973)

7. Technical Developments

a) On-line Measuring System

In late 1968 the bubble chamber group was given the use of the Photon group's PDP-8 computer for the construction of an on-line measuring system. The machine then consisted of a PDP-8 computer with 8K of core, teletype, 2 dectape drives, high-speed paper-tape reader and punch, and a Kennedy incremental tape drive. We wrote a time-sharing program for the PDP-8 to accept data from our measuring machines. This program guides the operator through the measurement of an event, changing views when appropriate. It checks the zeroing of the counters and performs a fiducial check to test the measurer and the functioning of the machine, and also has the capability of testing the smoothness of the measured tracks. Measurement data are written by the Kennedy tape drive event by event in card image BCD format.

We have added to the system hardware teletypes, teletype interfaces, and four interfaces appropriate to our two Data Tech image plane digitizers and two Vanguard film plane digitizers. Three of these machines are now on-line and working well. The electronics of the fourth machine, an older Vanguard film plane digitizer, is outmoded and unsuited to computer control. We have designed and are building new integrated circuit logic to completely replace the old electronics. This work is expected to be completed shortly, at which time we will totally commit ourselves to the on-line system and release our remaining keypunches.

b) SPASM

SPASM is a computer controlled cathode ray tube automatic scanning and measuring machine. It was originally built at Harvard by Dr. A. Brenner as a "poor-man's" POLLY. Like POLLY, it digitizes bubbles by making short sweeps of a point-like spot on the face of a precision CRT imaged on the film. Unlike POLLY, SPASM makes a single sweep for each computer command, but it can digitize as many as three bubbles per sweep.

The first model of SPASM, using a 5-inch CRT, was built by the Harvard group to digitize 35 mm spark chamber film. It was successful at this, and in fact, a Tufts spark chamber experiment was totally measured on SPASM. ⁽¹⁾ The Harvard group then decided to upgrade

SPASM to bubble chamber capability. In terms of hardware, this involved building an entirely new film scanner with a 7-inch CRT and a triplex film transport capable of simultaneously moving three views of 35 mm film. An operator's console was designed into the new system, acknowledging the elusiveness of the goal of a completely automatic measuring machine. This console contains an optical projection of the film to be measured, a storage/display oscilloscope for communications from the computer, a function box for commands from the operator, and a sonic pen that allows the operator to reference points on the film or the display unit. This console allows rather effective man-machine interaction. New software had to be written for the bubble chamber SPASM, and it was at this point that one of us (G.W.) began to take an active role in the development of SPASM, writing the software for the operator-machine interface.

After the construction of the new hardware was essentially completed, but before significant testing had begun, the SPASM project was transferred to Tufts. In early 1971, SPASM and its PDP-1 computer were dismantled, moved to Tufts and reassembled. When the system arrived, many of the separate sections of the operator's console were put together but, in fact, none were working, the film transport was intermittent and tore film, there were difficulties with the new CRT, and there were problems with the stability of the old electronics that were not critical to the lower precision spark chamber SPASM. Since this time, we have been working to make the system operational.

We had to first develop within the group the capabilities in electronics and digital logic to cope with the new hardware. Our early efforts were concentrated on the operator's console. The sonic pen logic had to be debugged, the preamplifiers discarded and a new design built from scratch, and the microphones rebuilt. The function box had to be wired. We bought a Tektronix 611 storage/display unit and interfaced it to the PDP-1. We repaired and modified the film transport so that it would move film under computer control without undue stress. The operator's console and film transport system are now fully operational.

Considerable progress has also been made on the measuring system itself. A back focus coil, already installed on the CRT to eliminate electron scattering off the elements of the electron gun, was not properly energized. We attached a separate stable current source to this coil, which made a substantial improvement in contrast, reducing noise, and also made the spot smaller. We noted stability problems in the bubble detection logic which were traced to the computer-type power supplies being used. When these were replaced by well-regulated supplies (acquired from government surplus) signal "jitter" was significantly decreased. Currently, we are working on the main deflection system, trying to improve short-term stability and to increase the current in the coils to fully utilize the 7-inch CRT and cover the three-view format.

At present, SPASM is able to scan good rolls from our 31" K⁻d exposure. Tests on sample frames of Argonne 12-foot chamber film also look highly encouraging. After we complete the work on the main deflection system we expect to begin production testing, and we will be able to come to grips with the questions of overall system stability and measurement accuracy that are crucial to the project.

Footnote

1. See Paragraph A of the Photon Group Section of this report.

Reports and Presentations

Bubble Chamber SPASM at Harvard. G. Wolsky (with authors from Harvard and Brandeis) in Proceedings of the Second International Colloquium on PEPR, Edited by Terence C. Watts (Massachusetts Institute of Technology, Cambridge, Massachusetts, 1970) p. 368

8. Computing

In the past the bubble chamber group has done its computer processing on three CDC machines; the 6400 of the Smithsonian Astrophysical Observatory, the 6600 at New York University and the 6600 at Brookhaven National Laboratory. This arrangement has been inefficient since we have had to maintain multiple copies of our programs and to do the bulk of our processing away from the Boston area. The latter problem was somewhat alleviated by our developing a data link (using the Tufts University IBM 1130 computer) to the New York University CDC 6600. This facility was made available to and used by other research groups in the Boston area. However, this system was too slow to allow economical bulk transmission of data or output.

In January 1973, Tufts University acquired a Decsystem 10 computer. The University also released its IBM 1130 thereby closing down our data link. We have made arrangements with the University administration to do our contract work on the Decsystem 10 computer. An acoustic coupler has been purchased enabling us to use the time sharing capabilities of the computer directly from a laboratory teletype. We are currently in the process of moving our computer load onto the Tufts machine. TVGP, SQUAW, ARROW and SODIT (the Tufts heavy liquid geometry program) are now operational on this new facility. We expect to increase our processing efficiency as all computer runs will take place on a single machine which is easily accessible.

Addendum

Since the writing of this progress report there have been additional developments concerning our Argonne National Laboratory K^+p experiment. The group at the University of Massachusetts feels that, at present, they are overcommitted in their obligations and would not be able to supply sufficient effort to this experiment. They have therefore withdrawn from the collaboration.

We have been in contact with ANL and have expressed our interest in continuing this experiment. We feel the physics involved is still very well worth doing. However, this experiment is too large for Tufts, by itself, to obtain significant results in a reasonable time, without an increase in scanning personnel. Therefore we are endeavoring to form a new collaboration.

In the meantime one of us has participated in the final tuning of the RF beam for 6.5 GeV/c K^- mesons. The tuning went smoothly and we learned a great deal concerning the operation of this beam. For our experiment the tuning is expected to be easier due to the higher K^+ yields.

TUFTS PHOTON GROUP
SUMMARY OF RESEARCH
1969 - 1973

Staff: Prof. Milburn, Asst. Prof. Rutherford, Asst. Prof. Quinn (1970-). Dr. Stottlemeyer (1973-); also Asst. Prof. Sinclair (-1969), now at SLAC).

Students: Mr. Shupe (1971-), Mr. Mroczkowski (1973-); also Mr. Tanaka (Ph.D. 1969, now at Los Alamos), Mr. Sauer (Ph.D. 1970, now at NAL), Mr. Castro (-1971, now at Tufts New England Medical Center), Ms. Kretschmer (M.S. 1969), Ms. Forey (M.S. 1969).

During the period 1969-1973 the Photon group has concentrated its activities in the field of photoproduction at high energies with a particular emphasis on polarization phenomena in forward pseudoscalar and vector meson production. We have utilized, in different experiments, both polarized-photon and recoil-spin-analysis measurements and have employed a variety of techniques including counters, optical and wire spark chambers and back scattered laser beams as were appropriate to achieve our results. Our work during 1969-73 is summarized in Table I and will be described in following paragraphs.

In the completed experiments listed in this table the photon group has played an essential role in achieving the highest energy measurements yet made of recoil proton polarization in π^0 photoproduction in and above the resonance region ($E = 1.5 - 1.8$ GeV, and 4.7 GeV), of two-body photoproduction with polarized photons (16 GeV) and of γ than three-body photoproduction with polarized photons of any energy (the SLAC 82-inch HBC Laser-beam program). The last two of these accomplishments were based upon the use, for the first time in a data reduction environment, of two qualitatively new techniques in high energy physics. The Photon group hopes to be able to continue in this pattern as is indicated in our present preparations for future experiments.

Much of the Photon group's work, as shown in Table I, has been done in collaboration with workers from other laboratories, and we are grateful to have had the opportunity to cooperate with so many fine physicists and their students. We believe that in each such collaboration the Tufts group's participation, when weighted for quantity and character of our contribution, has been a major factor in the successful outcome of the research. We feel we have demonstrated that a relatively small group - averaging over past years 3-4 postdoctoral researchers and about the same number of students - can still, by careful selectivity, make significant and continuing contributions at the frontiers of high energy physics.

TABLE I

TUFTS PHOTON GROUP
SUMMARY OF RESEARCH 1969 - 1973

Part I: Completed/Essentially Completed Work

<u>Counter and Spark Chamber Experiments</u>		<u>Accelerator</u>	<u>Principal References with</u> <u>Tufts Authors (1969 - 73)</u> (additional references are listed in the text)
A.	p-polarization in $\gamma p \rightarrow \pi^0 p$ (Tufts-M.I.T. Collaboration)	1.0 - 1.8 GeV 62° c.m.s.	CEA Phys. Rev. <u>D8</u> , 1(1973) (completed)
B.	p-polarization in $\gamma p \rightarrow \pi^0 p, \gamma p$ (Tufts-M.I.T. Collaboration)	4.7 GeV .22 ≤ t ≤ .53 (GeV/c) ²	CEA and Cornell Phys. Rev. Lett. <u>29</u> , 1752(1972) (completed)
C.	(polarized- γ) _{p,d} → $\pi^+ N, \pi^+ \Delta, K^+ \Lambda, K^+ \Sigma$ (Tufts-SLAC Collaboration)	16 GeV t ≤ 0.8 (GeV/c) ²	SLAC Bonn Symposium Contributions #84, 85, 86, 91.(1973) (preliminary results) Phys. Rev. Lett. <u>30</u> , 1230(1973) IEEE Trans. Nucl. Sci. <u>20</u> , 447(1973)

TABLE I (continued-2)

	<u>Laser Beam Development and SLAC HBC Experiments</u>		<u>Accelerator</u>	
D.	Laser Beam systems development (Tufts-CEA Collaboration)	5-6 GeV electrons 600 MeV photons	CEA	IEEE Trans. Nucl. Sci. NS-16, 1069(1969) (completed)
E ₁ .	82-inch HBC Laser Beam development (Tufts-SLAC Collaboration)	19 GeV electrons 3-5 GeV photons	SLAC	IEEE Trans. Nucl. Sci. NS-16, 1065(1969) Nucl. Instr. & Meth. <u>75</u> , 220(1969) (completed)
E ₂ .	82-inch HBC Experiments (polarized- γ) on p: also i) total cross sections ii) to $\rho^0 p$ iii) to $\rho^0 p$ iv) to ωp v) to $\Delta\pi$ vi) ω - ρ^0 interference vii) $\pi^- + (\text{anything})$ viii) to $K^+ \Lambda$ and $K^+ \Sigma^0$	2.8 and 4.7 GeV 1.44, 2.8 and 4.7 GeV 2.8 and 4.7 GeV " " " " " " " " 2.8, 4.7, 9.3 GeV 2.8 and 4.7 GeV	SLAC " " " " " " " "	Phys. Rev. <u>D5</u> , 545(1972) Phys. Rev. Lett. <u>23</u> , 498(1969) Phys. Rev. Lett. <u>24</u> , 955(1970) " " " <u>24</u> , 960(1970) " " " <u>24</u> , 1364(1970) " " " <u>25</u> , 1223(1970) Nucl. Phys. <u>B29</u> , 349(1971) Phys. Rev. <u>D5</u> , 1603(1972) Bonn Symposium Contribution #228 (1973) (preliminary)

(Additional references are given in the text to analyses of the above exposure and of exposures on deuterium, without Tufts' authorship.)

Experimental Analysis of Pseudoscalar Meson Photoproduction Amplitudes

F.	Study of Polarization and Spin Correlation Experiments (Collaboration of J. Rutherford of the Photon Group and theorists from Tufts and the University of Oregon)		Nucl. Phys. <u>B57</u> , 18(1973) Bonn Symposium Contribution # 46 (1973) (preliminary)
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TABLE I (continued-3)

- G. Feasibility Study of Measurements of Polarization in (polarized- γ) $p \rightarrow k^+ \Lambda$ Nucl. Phys. B53, 197(1973)
(Collaboration of J. Rutherford with Tufts Theorists)

Part II: Current Work (9/73, proposed for continuation in 1974)

		<u>Accelerator</u>	<u>Status as of September 1973</u>
H.	(polarized- γ) $p \rightarrow \gamma p$ (presently a Tufts-M.I.T.-SLAC-U. Mass Collaboration)	6-12 GeV $ t \leq 1(\text{GeV}/c)^2$ SLAC	Proposal preparation; Cherenkov counter construction and test; design of experiment; program development; analysis of test run data.
I.	(polarized- γ) $p \rightarrow$ (strange particles) (further studies of Tufts-SLAC-LBL-UC-Berkeley data tapes from earlier laser beam runs)	SLAC	Finish $K^+ \Lambda$ and $K^+ \Sigma^0$ analysis, especially cross sections; summarize properties of 3-body final states.
J.	High-repetition-rate laser studies aimed at development of source for SLAC RCBC, streamer chamber, etc.		Power supply development nearing completion; initiate operating condition optimization measurements.
K.	Unification of resonance and Regge region data on $\gamma p \rightarrow \pi^0 p$; tests of semi-local duality (Collaboration with Tufts Theorists)		Generation of master data source tape.

A.

Recoil Proton Polarization in π^0
Photoproduction 1000-1800 MeV Near 60°

(Prof. R. Milburn, Asst. Prof. J. Rutherford, students N. Tanaka (Ph.D. 1969, now at Los Alamos), M. Castro (now at Tufts New England Medical Center); also Prof. M. Deutsch and colleagues at M.I.T.)

This experiment was conceived nearly 10 years ago and, after a major delay caused by the CEA explosion and fire, was run at CEA during 1967.

The reduction of the 150,000 carbon-plate spark chamber photographs used for proton polarization analysis was done initially by hand measurement on digitized projectors, permitting preliminary results to be obtained and reported in 1969 (refs. A1, A2, A3). At this time Prof. Rutherford and Mr. Castro adapted the Harvard SPASM system (now at Tufts) to effect the automatic measurement of these pictures. Complete and final results were reported to the 1972 HEP Conference (ref. A4) and have since been published (ref. A5).

The data from this experiment are summarized in Fig. A1 (ref. A5) in which are also plotted earlier results from CalTech which overlap our measurements at the lower energies. Our most significant finding is the existence of a well-defined zero in the recoil proton polarization in π^0 photoproduction near 63° center-of-mass pion angle for all incident photon energies 900-1600 MeV.

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- A5 N. Tanaka, et.al. Phys. Rev. D8, 1(1973)

Tufts Publications

Recoil-Proton polarization in Neutral Pion Photoproduction
Between 1000 and 1800 MeV. N. Tanaka, M.M. Castro, R.H. Milburn,
W.B. Richards J. P. Rutherford, and B.F. Stearns, Tufts
University; M. Deutsch, P.M. Patel and K. Tsipis of M.I.T.
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Recoil Proton Polarization in Neutral Pion Photoproduction between
1200 and 1800 MeV . M. Castro, R. Milburn, W. Richards,
J. Rutherford, C. Sinclair, B. Stearns and N. Tanaka, with authors
from M.I.T. Bulletin Amer. Phys. Soc. 14, 44(1969) Paper BI4.

M. Castro, R. Milburn, W. Richards, J. Rutherford, C. Sinclair,
B. Stearns and N. Tanaka, with authors from M.I.T.. Contribution
to 1969 International Symposium on Electron and Photon Interactions
at High Energies, Daresbury, England, Sept. 14-20, 1969.
Abstract No. 13.

Recoil Proton Polarization in Neutral Pion Photoproduction between
1000 and 1800 MeV. N. Tanaka, M.M. Castro, R.H. Milburn, W.B. Richards,
J.P. Rutherford and B.F. Stearns, and authors from M.I.T..
Contribution to XVI International Conference on High Energy Physics,
(1972)

FIGURE A1: Recoil proton polarization dependence on pion production angle for different photon energies; data from this experiment and from earlier Caltech work near 60° (from ref. A5). Not shown in this particular figure is a single Tufts point $P = -0.2 \pm 0.5$ at 62.6° and a mean energy 1680 MeV to represent the 1600-1800 MeV results.

B. Recoil Proton Polarization in High Energy
Neutral Pion Photoproduction and in
Proton Compton Scattering.

(Asst. Profs. Quinn and Rutherford; also Prof. M. Deutsch,
 Dr. P. Kijewski, Messrs. L. Golub and D. Potter of M.I.T.)

Of all the two-body pseudoscalar meson photoproduction processes, the reaction $\gamma p \rightarrow \pi^0 p$ should be the simplest theoretically because of the limited number of possible exchanges. Through 1968 there existed cross section data and limited polarized photon asymmetry data at small angles. Various models of the Regge pole type with absorption could reproduce the data but differed wildly in the structure of the underlying amplitudes and hence in their predictions for other observables for this reaction.

In December of 1968 it occurred to us that our understanding of this reaction could be greatly advanced by data on the recoil proton polarization. Since the Tufts group had measured proton polarizations before, it was natural for us to pursue this idea. In the spring of 1969 we entered into a collaboration with Martin Deutsch of M.I.T. and began detailed calculations and equipment construction. Our formal proposal was accepted by the C.E.A. in the fall of 1969 and we began to set up on the experimental floor. The January 1970 decision to cut C.E.A. operating funds in June caused us to rush our preparations but we succeeded in taking some data in March and April in a parasite beam.

The kinematic range and statistics of these data were quite limited so a proposal was submitted to Cornell to finish the experiment. This was accepted in December of 1970. We moved our equipment to Cornell in May of 1971, set it up in June, had some test beam in July and had three long weekends of production running in August and early September. Preliminary results were submitted to the Annual Meeting of the APS in February of 1972. (ref. B1) Many consistency checks were performed on the data before final publication (ref. B2). Figure B1 summarizes the principal results of this experiment.

The equipment for this experiment included a lead-glass array with a scintillation hodoscope in front to detect one or both of the gammas from π^0 decay or the recoil Compton gamma. The recoil proton was detected in a range telescope. The absorbers in the telescope were made of graphite plates and scintillation counters and were interleaved with wire spark chambers. Proton scattering in the carbon provided a measurement of the proton spin polarization. The experiment was controlled by a PDP-11 computer which recorded the data on magnetic tapes and performed various checks on-line.

In the proton Compton scattering reaction ($\gamma p \rightarrow \gamma p$) the data cover the range $0.22 \leq |t| \leq 0.53 \text{ GeV}^2$ at an average incident photon energy of 4.7 GeV. The results over this range are consistent with zero or slightly positive polarization. If Compton scattering is indeed dominated by the diffractive processes, then the polarization is a measure of the real part of the nucleon spin-flip amplitude. Our data set an upper limit on the size of this amplitude.

Of greater interest and constituting the primary goal of the experiment are the results for neutral pion photoproduction ($\gamma p \rightarrow \pi^0 p$). Here our data cover the range $0.22 \leq |t| \leq 0.64 \text{ GeV}^2$. The predictions of the conventional Strong Cut Regge Absorption Models (SCRAM) are totally inconsistent with our data. Such models must now be drastically altered or thrown out. Weak cut models agree in general features but have difficulty accounting for the large negative values near $|t| = .6 \text{ GeV}^2$ where the dip in the cross section occurs. Even Harari's Dual Absorption Model (ref. B3) successful in so many two-body reactions, fails to fit our data.

As we were completing our data taking, Daresbury presented their new polarized target data for this reaction at the Cornell Conference in August of 1971 (ref. B4). This parameter is constrained by the polarized-photon asymmetry data to be very similar to ours. The Daresbury data differed at both small $|t|$ and at large $|t|$ from our results. The large $|t|$ difference is no more than is allowed but is theoretically surprising because no exchange particle is known to exist to cause this difference. (We hope to shed more light on this possible new exchange with future experiments.)

The small- $|t|$ difference is inconsistent with the polarized photon asymmetry. One of the three experiments must be wrong. DESY presented data at the NAL Conference of 1972 on recoil proton polarization in π^0 photoproduction in the low $|t|$ region which agreed beautifully with our data (ref. B 5). More recently another group at DESY has presented results on their polarized target measurement which is very similar to the Daresbury data except in the low $|t|$ region where the agreement with our data is acceptable (ref. B 6).

Professors G. Goldstein and J. Rutherford have recently published an amplitude decomposition for neutral pion photoproduction at high energies using all the data available for this reaction (ref. B 7). In principle, data on seven observables are necessary to determine the amplitudes while data on only four are available. However, because of the extreme values of some of the asymmetries it has been possible to deduce the general amplitude structure if a few weak assumptions are made. More recently, a group of theorists at McGill have done the same thing but have included the constraints imposed by the resonance region data through the FESR (ref. B 8). Their solutions are nearly identical to ours. Another attempt is in progress at Daresbury using slightly different assumptions (ref. B 9).

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Unpublished Reports

Recoil Proton Polarization in Pion Photoproduction and Compton Scattering Near 5 GeV. D.J. Quinn and J.P. Rutherford (with Authors from M.I.T.) Bulletin of the American Physical Society 17, 104(1972) Paper HH4

Polarization of the Recoil Proton in the Reactions $\gamma p \rightarrow \pi^0 p$ and $\gamma p \rightarrow \gamma p$. D.J. Quinn and J.P. Rutherford, (with authors from M.I.T.) M.I.T. Report No. C00 3069 - 71

POLARIZATION

FIGURE B1

The upper graph shows our recoil proton polarization data in neutral pion photoproduction. For comparison the Target Asymmetry data of Reference B4 are included. The difference between the two sets of data is constrained by the polarized photon asymmetry.

POLARIZATION

The lower graph shows our results for Proton Compton Scattering. The result is consistent with zero for all t .

C. Polarized Photon Asymmetries in
Pseudoscalar Meson Photoproduction
at 16 GeV

(Asst. Profs. Quinn and Rutherford, Mr. Shupe;
 also Drs. Sherden, Siemann and Sinclair from SLAC.)

An experiment to measure the photoproduction of charged pions and kaons with a high energy, linearly polarized photon beam was undertaken in the summer of 1972. For this experiment, a new linearly polarized photon beam was designed and constructed (ref. C1). The beam made use of coherent pair production in crystalline graphite to absorb preferentially one linear polarization from an initially unpolarized 16 GeV bremsstrahlung beam, thus transmitting an attenuated linearly polarized beam (ref. C2). The polarization was measured by passing the beam through a second assembly of crystalline graphite, measuring the ratio of the beam intensities as a function of photon energy when the two assemblies were in the crossed and aligned positions.

The beam was measured to have a polarization of 0.255 ± 0.020 over the region 14 to 16 GeV, and an energy spectrum similar to bremsstrahlung in this region.

We measured the final states $\pi^{\pm}N$, $\pi^{\pm}\Delta(1236)$, $K^+\Lambda$, and $K^+\Sigma$ from both hydrogen and deuterium targets. Momentum transfers (t) from -0.002 to -1.5 GeV^2 were measured, though not all reactions were measured at every angle. In all, we obtained over 90 data points covering the above reactions. We measured the cross sections as well as the polarized photon asymmetries.

Concerning polarized photon asymmetries, this represented the first measurement for the reaction $\gamma p \rightarrow \pi^+ p$ above 3.4 GeV, the first measurement ever for $\gamma p \rightarrow K^+ \Lambda$ and $\gamma p \rightarrow K^+ \Sigma^0$, and the most detailed and statistically accurate measurements for $\gamma N \rightarrow \pi^{\pm} \Delta$.

These data were submitted to the Bonn Conference on Electron and Photon Interactions in August 1973. Some have been published and the rest is in the process of being prepared for publication. We indicate here the highlights of our findings.

Polarized photoproduction of pseudoscalar mesons is useful for determining the parity sequence of the particle exchanged between the baryon and the photon-meson system. For photons polarized in the plane of the reaction, only unnatural parity ($p = -(-1)^J$) objects can be exchanged, while perpendicular photons contribute only to natural parity exchange. The above holds to lowest order in t/s . For pion production, it is useful to use both hydrogen and deuterium targets, since the interference term between positive and negative G parity exchange (corresponding to incident isoscalar and isovector photons respectively) changes in going from proton to neutron initial states.

The figures summarize the results of this experiment. Figure C1 shows the natural parity and Figure C2 the unnatural parity exchange contributions to these reactions. It can be seen that the momentum transfer structure is quite different in these two cases. For instance, the unnatural parity contribution to $\gamma p \rightarrow \pi^+ n$ and $\gamma n \rightarrow \pi^- p$ has a deep dip at $t \approx -m_\pi^2$, while the natural parity part is featureless, as would be expected from pion exchange. (It is interesting to note that the same qualitative behavior was found for the sum of reactions $\gamma p \rightarrow K^+ (\Lambda \text{ or } \Sigma^0)$, with the unnatural parity zero appearing at $t \approx -m_K^2$).

By combining our measurements of single pion photoproduction with earlier polarized photon measurements below 3.4 GeV (ref. C3) and measurements of energy dependence from 5 to 16 GeV (ref. C4) we were able to extract the Regge effective $\alpha(t)$ appearing in the formula

$$\frac{d\sigma_{N,\nu}}{dt} = \beta_{N,\nu}(t) S^{2\alpha_{N,\nu}(t) - 2}$$

We found for both single π^+ and π^- production, that the natural parity $\alpha_N(t) \approx 0$ for all t 's measured, while $\alpha_\nu(t)$ is consistent with the prediction from simple pion Regge pole exchange, $\alpha_\nu(t) \approx t - m_\pi^2$ when the units are GeV^2 .

The four $\gamma N \rightarrow \pi \Delta$ reactions we measured contain a wealth of information. The ratio of $\pi^+ \Delta$ or $\pi^- \Delta$ production from deuterium to hydrogen gives a measure of the contribution of exchanges with isospin two. We observed indications of these exchanges in both parity states for $\gamma N \rightarrow \pi^+ \Delta$, which would rule out the exchange of a single exotic particle which would have definite parity sequence.

The $\pi\Delta$ reactions have a rich and varied structure in the intermediate t region. The π^-/π^+ ratios from deuterium indicate a large isoscalar-isovector photon interference in both parity states.

For $|t| \gtrsim 0.8(\text{GeV})^2$, all the reactions measured are dominated by natural parity exchange. The t dependence is simple ($\sim e^{3t}$), and the s dependence has an effective Regge α near zero. Furthermore, all these cross sections are of the same order of magnitude. The reaction $\gamma p \rightarrow \pi^0 p$ shares these features (ref C5). This simple behavior does not come in a simple way from current models of high energy reactions, and thus presents a challenge to the theorist.

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 Contributions to the 1973 International Conference on
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 Germany, 1973:

- 1) Polarized Photon Asymmetries in 16-GeV charged Pion Photo-
 production for Momentum Transfers $|t| \lesssim m_\pi^2$; #84
- 2) Asymmetries in the Photoproduction of $\Delta(1236)$ from Hydrogen
 and Deuterium by 16 GeV polarized Photons; #91
- 3) Polarized Photon Asymmetries in K^+ Photoproduction at
 16 GeV; #86
- 4) Asymmetries in Charged-Pion Photoproduction on Nucleons
 by 16-GeV Polarized Photons; #85

The above four papers were also submitted to the Divisional
 Meeting of the American Physical Society, Division of Particles
 and Fields, Berkeley, California, 1973, where they were contributions
 number 165, 164, 166 and 163 respectively.

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FIGURES C1 and C2

Schematic plots of the cross sections measured with 16 GeV photons polarized perpendicular and parallel to the reaction plane. The reactions $\gamma p \rightarrow \pi^- \Delta^{++}$ and $\gamma p \rightarrow \pi^+ \Delta^0$ have been omitted for simplicity. The natural parity exchange cross sections (perpendicular photons) are roughly proportional to $(S - m^2)^{-2}$, in all cases where the energy dependence has been measured.

D/E

Laser Beam Development and SLAC
HBC Laser Beam Experiments

(Participants during 1969 - 73)

D: Systems development at CEA: Prof. Milburn, Asst. Prof. Sinclair (now at SLAC), Mr. Sauer (Ph.D., 1970, now at NAL); also Dr. Fotina of CEA.

E₁: HBC Laser Beam at SLAC (development): Asst. Prof. Sinclair, (now at SLAC); also Scientists and Engineers from SLAC and LBL.

E₂: SLAC 82-inch HBC Experiments: Prof. Milburn; also many scientists from SLAC, LBL and UC-Berkeley.

The practical use of compton scattering of laser light on energetic electrons to produce very high energy and highly polarized gamma rays was an early invention and development by the Tufts high energy group (refs. D1, D2, D3). Subsequent work at the CEA led to a detailed understanding of the practical requirements associated with laser and light-injection systems appropriate to the generation of useful high energy photon beams by this technique. This work also led, incidentally, to a new diagnostic tool for high energy electron beams. (ref. D4).

Most significantly, and thanks particularly to the efforts of Dr. Sinclair, then at Tufts, and of scientists from SLAC and LBL, the technique has made possible the creation of a source of highly polarized and nearly monochromatic gamma rays which has been used in a major series of bubble chamber exposures in the SLAC-LBL 82-inch chamber (ref. E1, E2). These exposures, which continued from 1969 to 1973, and yielded more than 4 1/2 million pictures, are listed in Table II. In six distinct series of exposures made for a comparable number of analysis collaborations, the photon energies covered the range from 0.6 to 9.3 GeV on both hydrogen and deuterium targets.

TABLE IISLAC LASER BEAM UTILIZATION

<u>SLAC Proposal Number</u>	<u>Energy (GeV)</u>	<u>Target</u>	<u>Appx # Pictures</u>	<u>Experimenters' Institutes</u>
BC-11	2.8	p	294,000	SLAC, LBL, UC-Berkeley, Tufts
	4.7	p	454,000	
	9.3	p	1240,000	
BC-18	4.25	d	505,000	Weizmann Institute
BC-6	3	d	500,000	U. Tennessee
BC-19	7.5	d	430,000	Tel Aviv
BC-35	3.5 & 5.5	d	412,000	UC-Berkeley - LBL
BC-47	0.6 - 1.2	p	468,000	SLAC, LBL
	0.6 - 1.2	d	220,000	

Total: 4,723,000

The analysis of the vast amount of data in these pictures is continuing to occupy the attention of groups and individuals at all the participating institutions. The most complete results so far published are from the hydrogen exposures. Prof. Milburn participated intimately in the analysis of these exposures during 1969-70 at Berkeley, and has continued to work on the strange-particle channels (see paragraph I, below). These hydrogen results form a large and unique body of information on many aspects of 2-body and multi-body photoproduction at energies 2.8 - 9.3 GeV with both polarized and unpolarized photons. Measurements have been reported, with Tufts co-authorship, on the total photon cross section on protons (ref. E3), on the cross sections for and mass shift in ρ^0 meson production (ref. E4), on natural parity exchange dominance and s-channel helicity conservation in ρ^0 meson production (ref. E5), on cross sections for natural and unnatural parity exchange contributions to ω -photoproduction (ref. E6), on cross sections and decay density matrices for Δ^{++} and Δ^0 production (ref. E7), on $\rho^0\omega$ interference parameters in photoproduction (ref. E8), on the inclusive reaction $\gamma p \rightarrow \pi^+ + (\text{anything})$ at 2.8, 4.7 and 9.3 GeV (ref. E9), and on preliminary results showing large positive polarization asymmetries in $K^+\Lambda$ and $K^+\Sigma^0$ photoproduction at 2.8 and 4.7 GeV, (ref. E10). A long paper has been published in the Physical Review giving an exhaustive description of the exposures at 2.8 and 4.7 GeV, and of the deduction of results from the particular reaction $\gamma p \rightarrow \pi^+\pi^-\pi^0 p$ (ref. E11). Figure E 1 illustrates certain salient features of this experiment and its results.

Workers at SLAC, LBL and UC-Berkeley are continuing to report new results from these exposures and from the extended runs at 9.3 GeV. For example, a recent contribution to the 1973 IUPAP Electron-Photon Symposium at Bonn extracts a polarized, diffractively produced $\rho'^+ \rightarrow \pi^+\pi^+\pi^-\pi^-$ signal at about 1.5 GeV from the 5-body process $\gamma p \rightarrow \pi^+\pi^+\pi^-\pi^- p$ (ref. E12). Moreover, results from the deuterium runs are only now beginning to be reported by the groups concerned (refs. E13, E14).

It has been a source of no little pleasure to the Photon group not only to have had a primary part in developing and establishing the laser beam technique in high energy physics, but also to have played a continuing though much smaller role in developing new elementary particle data from exposures using this technique. Our success is best witnessed, we believe, by the stream of new results this technique has made possible.

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Polarization Phenomena in $K^+ \Lambda$ and $K^+ \Sigma^0$ Photoproduction by
2.8 and 4.7 GeV Polarized Photons in a Hydrogen Bubble Chamber.
R.H. Milburn with authors from SLAC, LBL and UC-Berkeley,
Contribution No. 228 to International Symposium on Electron and
Photon Interactions at High Energies, Bonn, Germany, 27-31 August,
1973.

also:

Preliminary versions of the SLAC-HBC-Laser Beam results listed
under Publications, above, were contributed to a number of
American Physical Society and other meetings: Bull. Amer. Phys. Soc.
Sect. II, 15, 580-581(1970) (3 papers); 15, 1634(1970); 16, 40(1971);
16, 549(1971) (2 papers); the 1969 Boulder Conference;
the 1969 Daresbury Symposium (abstracts No. 109 - 111).

FIGURE E1

HBC-Laser-Beam Experiments
Representative Results

(i) (right) Photon energy spectra for exposures at (a) 2.8, (b) 4.7, and (c) 9.3 GeV. (from ref. E9)

(ii) (below) Reaction $\gamma p \rightarrow p \rho^0$ at 2.8 GeV. ρ^0 -angular decay distribution in the helicity system without background subtraction. The figure illustrates both the high photon beam polarization and the conservation of s-channel helicity in this process. (from ref. E11)

(iii) (below, right) Reaction $\gamma p \rightarrow p \pi^+ \pi^-$; combined $\pi^+ \pi^-$ distributions at 2.8 and 4.7 GeV. The figure shows fits with and without inclusion of ρ^0 - ω interference. (from ref. E11, E8)

PHOTON ENERGY SPECTRA

(continued)

$$\gamma p \rightarrow p \rho^0$$

(iv) (right) Parity asymmetry P_G and production polarization asymmetry Σ for $\gamma p \rightarrow p \rho^0$ at 2.8 and 4.7 GeV. The figure illustrates the dominantly diffractive nature of ρ^0 -photoproduction. (from ref. E11)

(v) (below) Test of s-channel helicity conservation in $\gamma p \rightarrow p \rho^0$. The angle β is that angle by which the ρ -decay density matrix as calculated in the helicity frame must be rotated about the production normal to minimize the "helicity-flip" terms and thus most closely simulate the photon. The helicity frame is seen to be favored (H). Were the Adair (A) or Gottfried-Jackson (GJ) frames favored the data would tend to lie along the (A) and (GJ) curves in the figure. (from ref. E11)

(vi) (right) Production asymmetry of $\gamma p \rightarrow K^+ \Lambda$, $K^+ \Sigma^0$ by polarized photons at 2.8 and 4.7 GeV. The figure illustrates the preponderance of K^+ emission in a plane perpendicular to the electric vector of the incident photon. (from ref. E10)

F.

Study of Polarization and Spin
Correlation Experiments

(Asst. Prof. Rutherford; with Asst. Prof. Goldstein and
J. Owens of Tufts Theory Group, and Prof. M. Moravcsik of
the University of Oregon)

In recent years polarized photon beams have improved considerably in quality and in ease of use. Also, polarized targets can now achieve high polarizations and are far better understood. Finally, techniques in recoil baryon polarization measurement are highly developed. To date, photoproduction experiments have used at most one of these techniques at a time. However it should be possible very soon to use two or all three techniques simultaneously. The spin-correlation measurements possible from such experiments could, in principle, uncover structures in the individual reaction amplitudes, information impossible to obtain with polarization and cross section measurements alone except in certain special cases.

Because such experiments have not proven feasible until recently, very little was known about the best experimental approach to pursue in such measurements. After preliminary work (ref. F1) we have just completed such a study and a detailed paper has been submitted for publication (ref. F2). We looked in detail at the pseudoscalar meson photoproduction amplitudes that contribute to each of the numerous observables which one can measure with combinations of all three techniques. We also calculated many constraints based on the interconnections between these observables.

These studies have, and will continue, to serve as an invaluable guide to us in planning for future experiments. We were surprised to find for most reactions in which polarization data exists, that, of the many possible correlation measurements, only a very few prove to be significant. This judgment was made in terms of what new information such experiments could bring to bear on determining the underlying structure of the amplitudes. We can thus say which of the many possible experiments will be useful and which won't be useful. Such information was not previously known and has already proved useful to us -(see paragraph G, below)

✓

We are continuing to develop pertinent and possibly indispensable theoretical relations which will, we believe, serve as invaluable guides to the proper planning of efficient future polarization and spin correlation experiments.

References and Tufts Publications

- F1 G.R. Goldstein, J.F. Owens, J.P. Rutherford, Polarization Predictions for K^+ Photoproduction Nucl. Phys. B53, 197(1973)
- F2 G.R. Goldstein, J.F. Owens, J.P. Rutherford, M.J. Moravcsik, Spin Correlation Measurements in Pseudoscalar Meson Photo-production. Contributed paper no. 46 to International Symposium on Electron and Photon Interactions at High Energies, Bonn, 1973. (submitted for publication)

G.

Feasibility Study of Measurements of Λ
Polarization in the Reaction
(Polarized γ) + p $\rightarrow$ K $^+$ Λ

(Asst. Prof. Rutherford and Mr. Shupe; with Prof. Goldstein
 and Mr. Owens of Tufts Theory Group)

In the fall of 1971 we began an exhaustive feasibility study of both the theoretical aspects and the apparatus design of an experiment to measure the polarization of the recoil lambda in the reaction $\gamma p \rightarrow K^+ \Lambda$ at small angles and at high energies where the incident photon has a high degree of linear polarization. The experiment was intended to be the first using the newly constructed, collimated, thin-diamond beam at SLAC (ref. G1) and to be the first high-statistics double-correlation experiment in pseudoscalar meson photoproduction. A test run at SLAC was approved for initial background studies. The theoretical considerations have been published (ref. G2). A number of detailed experimental configurations were designed and their performance simulated by Monte Carlo programs. During the summer of 1972, we learned three facts; first, our measurements of the polarized photon asymmetry, Σ , in KA photoproduction (see paragraph C, above) showed this observable to be almost unity over a large range in t; second, an experiment at DESY measured the recoil lambda polarization in this reaction with an unpolarized beam and found a very large negative polarization over a wide range in t (ref. G3); and finally, our study of polarization and spin correlation experiments (see paragraph F, above) has shown us the interconnections between the measurements we proposed to make and the measurements already made during 1972. We found that the proposed experiment would not yield the wealth of information we had originally anticipated because of the unexpected results from the measurements just completed. We therefore decided to drop further feasibility studies of this experiment and to shift our emphasis to a newer, less-explored field. We believe this experience demonstrates the power of the general spin-correlation analysis formulation of the preceding paragraph.

References

- G1 W. Ash, et.al. A High Intensity Partially Monochromatic Polarized Photon Beam at SLAC, contributed Paper no. 66 to International Symposium on Electron and Photon Interactions at High Energies, Bonn 1973.
- G2 G.R. Goldstein, J.F. Owens, and J.P. Rutherford, Polarization Predictions for K^+ Photoproduction, Nucl. Phys. B53, 197(1973)
- G3 G. Vogel, et.al. Phys. Letters 40B, 513(1972)

Publication

Polarization Predictions for K^+ Photoproduction,
J.P. Rutherford (with Tufts Theorists G.R. Goldstein
and J.F. Owens) Nucl. Phys. B53, 197(1973)

H. High Energy Eta Photoproduction with Linearly
Polarized Incident Photons

(Professors Milburn, Rutherford, Quinn, Dr. Stottlemeyer,
Mr. Shupe in collaboration with M. Deutsch of M.I.T.
M. Rabin of U. Mass, and D. Sherden of SLAC.)

As noted in paragraph B, the reaction $\gamma p \rightarrow \pi^0 p$ should be the simplest of all the pseudoscalar meson photoproduction reactions from a theoretical standpoint because of the limited number of exchanges. The reaction $\gamma p \rightarrow \eta p$ shares this distinction of simplicity since the π^0 and the η meson occupy the same position in the SU(3) nonet. However, the coupling strengths of the limited exchanges should be different. Reasonable predictions suggest that η -photoproduction will proceed via a much larger unnatural parity contribution than occurs in π^0 production (ref. H1). Recently, very unusual behavior of unnatural parity parts has been observed by this group (see paragraphs B and C above). However, these experiments were insensitive to the detailed behavior of the unnatural parity contributions since the latter have turned out to be small in all reactions measured to date. A large unnatural parity cross section in η -photoproduction will allow us to study this unusual behavior with much better sensitivity.

We began feasibility studies for performing such an experiment during the summer of 1972. We intend to use the new collimated thin diamond beam which Prof. Rutherford helped test out and measure in January of 1973 (ref. H2). This beam is quasi-monochromatic and highly polarized. The quasi-monochromaticity greatly reduces the background from the competing process $\gamma p \rightarrow \pi^0 p$ and also minimizes the low energy junk. This gives us hope of performing a coincidence measurement. We intend to detect the recoil proton in the SLAC 1.6 GeV/c spectrometer and to detect one of the decay photons of the eta in a lead-glass "fly's eye" hodoscope. We have performed two test runs at SLAC in which we studied the background problems encountered in the lead glass detector. We have already purchased a large fraction of the hardware and electronics for this experiment and anticipate that such a piece of apparatus will also be useful in many different experiments in addition to that under immediate consideration.

Dr. Stottlemeyer (who began work at Tufts in August 1973) is currently redesigning the Cherenkov counter's phototube bases to optimize the possible timing resolution which can be achieved consistent with pulse-height resolution. Prof. Milburn is designing a light pulsing system to permit on-line testing and energy calibration of this counter.

Mr. Shupe has designed, built and successfully tested a number of CAMAC-oriented modules which can interface our existing LeCroy readout systems to CAMAC, and a manual run-control panel to CAMAC, and also a PDP-11/XDS-9300 interface via CAMAC controllers associated with each system. These devices will permit us to attach our 48-element Cherenkov counter hodoscope to SLAC's on-line XDS-9300 controlling and logging processor with a minimum of interference to existing SLAC systems. It will also greatly facilitate off-line testing and alignment of this complex counter system.

Prof. Milburn has, with the help of M. Hecht, a Princeton undergraduate, finished development of a DECTAPE library system to facilitate program development, storage and loading on our PDP 11 processor. He has also developed a set of FORTRAN and MACRO routines which permit the analysis of XDS-9300 packed binary data logging output tapes by means of an interactive, time-sharing terminal connected to Tufts PDP-10 Computing Center. This system is presently being used to analyze data from earlier test runs at SLAC, and will be of obvious utility in the event of a large-scale experiment there.

We intend to submit a formal proposal to SLAC this fall. The principal questions remaining concern our estimates of the operating intensities supportable in the presence of uncorrelated background processes, and hence of the magnitude of the background subtractions we must make. As this affects our statistical uncertainty we require better estimates to properly assign running times at the various kinematic points.

References

- H1. See for instance F.D. Gault, et.al., Nucl. Phys. B32, 429(1971)
- H2. W. Ash et.al. A High Intensity Partially Monochromatic Polarized Photon Beam at SLAC. Contributed paper no. 66 to International Symposium on Electron and Photon Interactions at High Energies, Bonn, 1973.

I. SLAC 82-Inch HBC Laser Beam Exposure:
Strange Particle Channels

(Prof. R. Milburn)

During the spring of 1973 Prof. Milburn reviewed the data summary tapes containing strange particle events from the 2.8 and 4.7 GeV SLAC 82-inch hydrogen bubble chamber laser beam runs. He was able to extract, from background processes, a clear signal of about 80 events identifiable separately as the reactions $\gamma p \rightarrow K^+ \Lambda$ and $\gamma p \rightarrow K^+ \Sigma^0$ at the two energies. These events showed a production asymmetry, Σ , with respect to the highly polarized incident photons, of nearly +1 for both reactions and both energies, and with momentum transfer parameter $|t| \leq 1.2 \text{ (GeV/c)}^2$. The large asymmetry enabled a good estimation to be made with relatively few events. Averaging both channels and energies, and including the range $0.25 \leq |t| \leq 1.2 \text{ (GeV/c)}^2$ for direct comparison with counter experiments at 16 GeV (paragraph C above), he found $\Sigma = +1.00$ at mean photon energy 3.67 GeV and $|t| = 0.63 \text{ (GeV/c)}^2$, with 68 percent and 95 percent confidence limits at $\Sigma = 0.82$ and 0.66, respectively. This asymmetry is the same, within statistics, as that observed in the $K^+ \Lambda$ and $K^+ \Sigma^0$ channels at 16 GeV. Additional study of the bubble chamber $K^+ \Lambda$ events was made to measure the polarization of the produced lambda particle as analyzed by its parity-violating decay. No polarization was detected within the large errors ± 0.6 . While not inconsistent statistically with the rather large $-(0.5 - 0.9)$, negative polarizations observed in a DESY counter experiment at 5 GeV (ref. I1), neither are the bubble chamber results comfortably confirmatory of the DESY work. An independent and more precise measurement of this important parameter is strongly suggested. These results were reported to the Bonn Symposium (ref. I2).

Although careful checking of possible systematic errors gives us confidence in the validity of these asymmetry and polarization results, above, we are less content with apparent discrepancies between the yields of $K^+ \Lambda$ and $K^+ \Sigma^0$ reactions in the bubble chamber and predictions based upon counter experiments using bremsstrahlung at SLAC (ref. I3). Prior to final publication we wish to make a more detailed study of the losses from scanning inefficiencies, finite

chamber size, measurement failures and other possible effects. We would also like, if possible, to include for completeness events from the 9.3 GeV exposure.

When the above study of two-body strange-particle reactions is finished we plan to survey and summarize the general features of the numerous multi-body strange-particle reactions remaining in this unique series of bubble chamber photographs. Within the large LBL-SLAC-UC-Tufts collaboration associated with the basic laser beam exposures, Prof. Milburn of Tufts and Prof. Hartwig Spitzer of the University of Hamburg are the scientists primarily concerned, at this writing, with the extraction of strange-particle results from the totality of measured events.

References

- I1 G. Vogel et.al. DESY Preprint 72/26(1972)
- I2 R.H. Milburn et.al. Contribution #228 to the International Symposium on Electron and Photon Interactions at High Energies, Bonn, (1973)
- I3 A.M. Boyarski, et.al. Phys. Rev. Letters 22, 1131(1969)

J. High Repetition-Rate Laser Studies

(Prof. Milburn, Mr. Mercurio (undergraduate 1970-72),
Mr. Mroczkowski (graduate student, 1973-))

The SLAC Laser-Beam bubble chamber exposures were based upon a large q-switched ruby laser whose maximum repetition rate of about 2 Hz matched the 2 Hz capability of the 82-inch SLAC HBC. Exposures in the latter of 294,000, 454,000, and 1,240,000 pictures yielded 92, 150 and 138 events/microbarn at 2.8, 4.7 and 9.3 GeV, respectively. It is clear that large-solid-angle experiments on reactions such as $\gamma p \rightarrow \Lambda K$ or $K \Sigma^0$, or on multi-body processes yielding $K^* \Lambda$, γp and other complex final states of microbarn or smaller cross section yielding good statistics and reaction-product acceptances would require systems capable of 60-120 Hz or faster operation. If such a system used a photographically recorded rapid-cycling bubble chamber or streamer chamber a selective electronic trigger would be necessary to keep the consumption of film within economic bounds. For a system of such nature to exploit the excellent polarization and quasi-mono-chromatic properties of the back-scattered laser beam would require a source laser yielding q-switched light pulses having energies of order of magnitude 1 joule each delivered at a repetition rate of 60-120 Hz. Such a laser has never been built. Hundred-watt lasers have been constructed to deliver output either CW or q-switched at rates above about 10,000 Hz. However, the desired combination of relatively large individual pulses with a repetition rate above 10-20 Hz imposes extraordinary demands upon the necessary optical pumping system in respect to both peak currents and average power dissipation.

Since 1970 Prof. Milburn, with the assistance of students, has been assembling and testing a prototype high-repetition-rate laser system based upon Nd-doped YAG and YALO crystalline rods. These materials were chosen because both materials have good thermal conductivity, involve a 4-level lasing system, and have worked satisfactorily in routine commercial applications at the 100-watt output level with a CW beam. The goal of this development research is to explore the problems of high-repetition-rate, high-average-power operation in sufficient detail to permit the establishment of optimal operating parameters for a system suitable to the repetition

rate/pulse-energy regime appropriate to SLAC. While it is possible that the Tufts system so optimized might itself serve as a basis for certain SLAC experiments, it more likely will be found to typify one module of a scaled up, multi-head laser source for a back-scattered SLAC beam.

During 1971-72 Nd-YAG and Nd-YALO laser heads were each brought into operation at low repetition rates (1-2 Hz) in normal and q-switched modes and in both oscillator and oscillator-amplifier configurations. The results of these tests were summarized in Applied Optics (ref. J1) and indicate that upwards of 0.5 joule output per q-switched output pulse can be obtained at a slope efficiency of at least 0.4 percent, and that a major problem lies in obtaining the necessary pump power input at the desired high repetition rates.

Work during 1973 has so far concentrated almost entirely on the electrical engineering problems of achieving a maximal average power input to the lamps (about 2 KW) pulsed at 60-120 Hz and of giving pump light output bursts shorter than 100-150 microseconds. The present, most reliable, system charges a 70 microfarad bank through a resonating choke and two high voltage SCR's in series. The bank is then discharged through the flashlamp by a coaxial ignitron switch whose function is to obviate difficulties associated with the failure of the lamp to de-ionize at high average powers. Serious difficulties were encountered in an earlier circuit through repeated failures of power diodes used to switch between the charging and discharging phases. The present system, in which the failing diodes have been replaced by a passive R-L circuit, has been operated for short periods at 60 Hz with about 2 KW power input. At present the pulsing circuits are being modified in a number of minor ways intended to reduce the undesirable excess power dissipation in the switching systems. A further engineering development is underway with the goal of reducing the light pulse below 100 or even 50 microseconds in length. This should reduce the effective threshold for lasing and thereby increase the repetition rate at which the system can give acceptable laser power output. It should also improve slope efficiency.

With a slope efficiency of 0.4 percent and a maximum average lamp power input of about 2 KW (governed by the heat dissipation at which the flashlamp walls begin to fail) the maximal light output from one of our laser heads is obviously about 8 watts, and probably less in consequence of lasing threshold effects. A two-lamp head

would raise this yield by raising the permissible power dissipation, though not by a full factor of two. It is evident that, say, a 30-watt output, 60 Hz unit might, with the present heads, require perhaps 6 such heads operating on one optical axis in a compromise regime with, say, each head delivering 0.5 joule pulses at 10 Hz (a purely illustrative example). Although the heads themselves are relatively simple and individually inexpensive, their cost in aggregate would be a major consideration in any system design. The goal of our developmental investigations is to put our knowledge of the properties of these laser units on a sufficiently firm empirical foundation to permit the sound specification of an optimal multielement system buildable at minimal cost. We mention here that we are also observing, with great interest, alternative approaches to the high-average-power, medium-repetition-rate laser problem, such as the use of dye lasers. We note that the United Aircraft Research Laboratories in Hartford has recently operated a 5 watt high repetition rate dye unit. This yield is comparable to what we expect from our YALO unit, albeit from a somewhat more complex overall system.

The current status of our work is that the electrical engineering problems associated with the pulser appear to be essentially solved so that optical measurements can begin during the last quarter of 1973 using 150-microsecond light pulses. Mr. Mroczkowski has successfully tested a concept for a parallel-triggering scheme which will reduce the lamp circuit inductance and permit shortening the light pulse. Following the long-pulse laser tests we shall implement this and measure its effects. We shall then expand the tests to include the simultaneous operation of both our lasers on one axis at fast repetition rates, both in two-head oscillator and in oscillator-amplifier configurations. No major equipment needs are anticipated, but it may prove necessary to repair damaged optical coatings, etc. Because of the many parameters involved and the imponderables associated with operating non-linear devices at high power levels it is expected that these tests will extend well into 1974. On the basis of this work, however we expect to be able to come to a firm conclusion about the practicality and cost associated with what could, if implemented, become a major new SLAC facility.

References

- J1. P. Mercurio and R.H. Milburn, Applied Optics 11, 2097(1972)

Tufts Publications

- Hybrid YAG-YALO Laser Operation at 1.064 μ . Paul Mercurio and Richard H. Milburn, Applied Optics 11, 2097 - 2100 (1972)

K. Experimental Tests of Duality

(Asst. Prof. Rutherford; with Assoc. Prof. Weaver and
Asst. Prof. Goldstein, of Tufts Theory group)

During the past five years we have been collecting data from the resonance region for pion photoproduction for comparison with the high energy data. The conjecture of Semi-Local Duality suggests that some average over the low energy data may bear significant resemblance to the high energy data. The reaction $\gamma p \rightarrow \pi^0 p$ may be a particularly good reaction with which to test this hypothesis. This is because the high energy cross section is probably dominated by a single amplitude which is mostly imaginary and because a great deal of data exist for this reaction both at high energies and at low energies.

Several comparisons in the past on small subsets of the data have given strong indications in support of the duality conjecture. We have recently obtained magnetic tapes of a DESY compilation of the low energy data and have finished adding all the new data of which we are aware. We have now started a detailed and exhaustive test of the duality conjecture. Besides our interest in testing the duality idea, we also expect that this study will help us choose between the many solutions generated by the various recent multipole analyses of the low energy data and used in FESR calculations.

Theory Group

(A.E.C. Support Terminated December 31, 1971)

Staff: Associate Professors Everett and Weaver, Assistant Professor Goldstein. Mr. Hajj (Ph.D. 1970 , now at Suffolk University) Mr. Hanlon (Ph.D. 1971 ,) Ms. Williamson (Ph.D. 1970 , now at Smithsonian Astrophysical Observatory), Mr. Owens (Ph.D. 1973, now at Case-Western Reserve).

Support of this group by the Atomic Energy Commission ended December 31, 1971. The group remains active, primarily through the support of Tufts University, and collaboration (sometimes very close collaboration) with the Bubble Chamber and Photon Groups continues. Below are listed those publications which resulted from the period of support by the AEC, 1969-1971.

Sum Rules in $\pi \Sigma$ Scattering and the $\pi \Lambda \Sigma$ and $\pi \Sigma \Sigma$ Coupling Constants. A.E. Everett, Phys. Rev. 177, 2561 (1969)

Validity of the Balazs Method. A.E. Everett and A. Antippa, Phys. Rev. 178, 2443 (1969)

ρ - f° Double Bootstrap by the Balazs Method. A.E. Everett and A. Antippa, Phys. Rev. 186, 1571 (1969)

ρ - f° Double Bootstrap Using the Veneziano Representation. A.E. Everett and A. Antippa, Phys. Rev. D1, 606 (1970)

Fredholm Character of the N/D Equations. A.E. Everett, Phys. Rev. D3, 2013 (1971)

Tachyons without Casual Loops in One Dimension. A.E. Everett and A. Antippa, Phys. Rev. D4, 2198 (1971)

S-Wave $\pi \pi$ Scattering in the Effective Potential Approximation. A.E. Everett, Phys. Rev. D4, 2797 (1971)

Bootstrap Calculation of the K^* Meson Using the Effective Potential Approximation. Phys. Rev. D5, 1681 (1972)

Publications (continued)

Wave Equations, Multipole Solutions, and Characteristic Hypersurfaces for Massless Particles. D.L. Weaver and J.P. Hajj, J. Math. Phys. 10, 1185 (1969)

Introduction to Low Energy Pion Photoproduction. D.L. Weaver, Frascati Report LNF-69/69.

An Energy Independent Multipole Analysis of Pion Photoproduction on Protons Below 450 MeV. D.L. Weaver and F.A. Berends, Nuclear Physics B30, 575 (1971)

Discussion of Isotensor Terms and T Violation in Pion Photoproduction near the First Resonance. D.L. Weaver and F.A. Berends, Phys. Rev. D4, 1997 (1971)

Multipole Radiation Solutions for a Class of Massive Particle Wave Equations. D.L. Weaver and J.P. Hajj, J. Math. Physics, 13, 640 (1972)

Pi Zero Photoproduction in a Weak Regge Cut Model. G. Goldstein and J. Owens, Phys. Rev. D7, 865 (1973)

A New Regge Absorption Model. G. Goldstein, R.L. Thews and J. Owens. Nuclear Physics B46, 557 (1972)

Polarization Predictions for K Photoproduction. G. Goldstein, J. Owens and J. Rutherford, Nuclear Physics B53, 197 (1972)

A Weak Regge Cut Model for $\pi N \rightarrow \rho N$. G. Goldstein and J. Hanlon, to be published in Physical Review.

Miscellaneous

Staff: Professor Cormack

During the period covered by this review the last three papers stemming from a collaboration with Lawrence Berkeley Laboratory and U.C. Santa Barbara appeared. They are listed below ¹⁻³.

There has been a recent explosion of interest in the problem of reconstruction of objects from their projections, a problem solved at Tufts in the early sixties. The problem occurs in several fields of medical physics, in astrophysics, in electron microscopy, and many other fields. The routine and successful hospital use of one solution of the projection problem was illustrated dramatically this summer on no less a patient than Dr. Paul Dudley White.

While the problem can be regarded as almost completely solved in two dimensions, interesting extensions to three dimensions have been remarked on, with a possible application in a novel method of positron annihilation scanning to locate brain tumors ⁴.

1. The Index of Refraction of Liquid Deuterium. A.M. Cormack, D.S. Ayres, D.O. Caldwell, V.B. Elings, A.J. Greenberg, W.P. Hesse, R.W. Kenney and R.J. Morrison, Physica 43, 105 (1969)
2. The Charged Pion Lifetime and a Limit on Fundamental Length. A.M. Cormack with D.S. Ayres et al., Phys. Rev. Letters 23, 1267 (1969)
3. Measurements of the Lifetimes of Positive and Negative Pions. A.M. Cormack with D.S. Ayres et al., Phys. Rev. D3, 1051 (1971)
4. Reconstruction of Densities from their Projections, with Applications in Radiological Physics. Phys. in Med. and Biol. 18, 195 (1973)