RECEIVED BY TIC DEC 4 - 1972

FINAL REPORT"EXPERIMENTAL PARTICLE PHYSICS PROGRAM"*

A brief summary of work accomplished during the contract period of a program in High Energy Physics at the University of Cincinnati.

Prepared by

Mirko M. Nussbaum
Professor of Physics

Department of Physics
University of Cincinnati
Cincinnati, Ohio 45221

NOTICE

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

*This program is being carried out with the support of the U.S. Atomic Energy Commission in the form of AEC SRSA Contract AT(11-1)-2090

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

FINAL REPORT"Experimental Particle Physics Program"INTRODUCTION

An experimental particle physics program was initiated in the Physics Department of the University of Cincinnati in September, 1969 with Professor Mirko Nussbaum as the Principle Investigator. A bubble chamber film analysis laboratory was set up with funds made available by the University of Cincinnati and supported by the Atomic Energy Commission via contract No. AT(11-1)-2090. The experimental high energy group included Assistant Professor Walter Carnahan from September, 1969 to June, 1971; Assistant Professor Robert Endorf joined the group in June, 1970. Three graduate students have worked in the group. They are Charles Horne, formerly a student with Professor Nussbaum from the University of Pennsylvania, Ann Johnson and P. Bapu. The experimental particle physics group has been involved in both bubble chamber and spark-chamber counter experiments.

RESEARCH PROGRAMA. Counter Experiments

When the A_2 boson was thought to be split it was interesting to determine whether the splitting represented a dipole resonance or an accidental proximity of two separate resonances. We undertook to study the structure of another member of the 2^+ octet, the $K^*(1420)$, which should also be split if the octet were made up of dipoles.

MASTER

An extensive counter-spark chamber experiment was completed in collaboration with the Halpern Group from the University of Pennsylvania early in 1971. The analysis was completed during the contract period and results submitted to Physical Review D. Our results showed lack of compelling evidence for splitting of the K^* . In the meantime, overwhelming experimental evidence shows that the A_2 is not split. Our results will appear in Physical Review D 6 (1972) under the title, "Production of Strangeness-one Bosons in the Mass Interval 1200-1600 MeV" (with Frati, et. al.).

B. Bubble Chamber Experiments

We have been engaged in a study of π^+d interactions at 8 GeV/c in collaboration with groups from Brookhaven National Laboratory, Oak Ridge National Laboratory, and the University of Tennessee. An exposure of 150,000 pictures of 8 GeV/c π^+ mesons in the BNL 80-inch deuterium bubble chamber was taken in 1970 to supplement an exposure of 150,000 pictures which had been taken earlier.

We have scanned 65,000 frames from the second exposure at the University of Cincinnati. All of the film from the second exposure has been scanned and the measurements are now being completed. Most of the measurements are being done on the University of Tennessee spiral reader; however some measurements have been made on a conventional measuring machine at the University of Cincinnati.

The analysis of the data is still in progress. Results which have been obtained and have either been recently submitted for publication or are now being prepared for publication are summarized below:

1. "Higher mass boson resonances in 7.87 GeV/c π^+d interactions." An examination of the boson mass distribution for all events of the type $\pi^+d \rightarrow p_s p x^0$, where x^0 represents any neutral bosonic state with four or less charged pions, shows clear enhancements in the f^0 , A_2 , g , $\phi(1670)$, and T mass regions. The enhancement in the T mass region has a statistical significance of four standard deviations and the significance increases to five standard deviations when even G-parity events are excluded from the mass distribution. The boson mass distribution has also been examined for each final state taken separately. A small enhancement in the T mass region was observed for all odd G-parity states. We conclude that there exists at least one state in the T mass region ($2.1 - 2.4$ GeV/c²) which has an odd G-parity and decays primarily into $\pi^+ \pi^- MM$. A small signal was seen for decays into $\pi^+ \pi^+ \pi^- \pi^- \pi^0$, $\pi^+ \pi^- \pi^0$, and all neutrals, but no evidence was found for a $\rho^0 \rho^0 \pi^0$ decay mode. A paper discussing these results has been accepted for publication and will appear on December 1, 1972 in Physical Review D1, Section 1, Vol. 6.

2. " $\rho\Delta$ production in π^+n interactions at 7.87 GeV/c." We have investigated the following $\rho\Delta$ reactions which decay into the final state $p\pi^+\pi^-\pi^0$:

$$\pi^+n \rightarrow \rho^+\Delta^0 \quad (1)$$

$$\pi^+n \rightarrow \rho^0\Delta^+ \quad (2)$$

$$\pi^+n \rightarrow \rho^-\Delta^{++} \quad (3)$$

Copious $\rho^0\Delta^+$ and $\rho^+\Delta^0$ production was observed, but little or no

$\rho^- \Delta^{++}$ production was seen. The ratio of the production and decay cross sections for reaction (2) to reaction (1) has been studied as a function t . This ratio (S) should be equal to one at all values of t for isovector exchange in the t -channel. We have found that the ratio S is approximately equal to 2 for $t < 8m_\pi^2$ and then drops to approximately equal to 1 for $t > 8m_\pi^2$. Background from other states can be shown to have a negligible effect on S . We have also found that the production of $\epsilon^0 \Delta^+$ is not sufficient to explain our results for the ratio S . A possible explanation for the deviation of the ratio S from one in the small t -region is that we are observing effects due to an $I = 2$ or double particle exchange mechanism. A paper describing these data is being readied for publication.

3. "Four pion decay of the f^0 meson." We have searched for a $\pi^+ \pi^+ \pi^- \pi^-$ decay mode of the $f^0(1260)$. A large $f^0 + \pi^+ \pi^-$ decay mode is observed in our data, but no significant $f^0 + \pi^+ \pi^+ \pi^- \pi^-$ decay mode is observed. We obtain an upper limit for the $f^0 + \pi^+ \pi^+ \pi^- \pi^-$ decay relative to the f^0 dipion decay of .033 with a confidence level of 90%. This value is in disagreement with the present world average of $.061 \pm .015$. A paper containing our results has been submitted for publication to Physical Review D.

C. Effort expended by Principal Investigator

During the contract period the Principal Investigator, Professor Nussbaum, has expended the following percentages of effort on the above research program:

50% effort - March, April, 1970

100% effort - May through September, 1970

50% effort - October, 1970 through April, 1971

100% effort - May through September, 1971

50% effort - October, 1971 through March, 1972

HIGHER MASS BOSONS FROM 7.87 GeV/c π^+ d INTERACTIONS*

W. M. Bugg, G. T. Condo, E. L. Hart
Department of Physics and Astronomy
University of Tennessee
Knoxville, Tennessee 37919

H. O. Cohn and R. D. McCulloch
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

R. Endorf, C. P. Horne and M. M. Mussbaum⁺⁺
Department of Physics
University of Cincinnati
Cincinnati, Ohio 45221

*Research jointly supported by the U.S.A.E.C. under contract with the Union Carbide Corporation and The University of Tennessee, Contract AT-(40-1)-3956 and the University of Cincinnati, Contract AT-(11-1)-2090.

⁺⁺ Present address: Department of Physics, Florida State University, Tallahassee, Florida.

ABSTRACT

By employing the 80" BNL deuterium bubble chamber as a missing mass spectrometer, evidence for an odd G parity state with a mass in the T region ($2.1 - 2.4 \frac{\text{GeV}}{c^2}$) is presented. Indications from the individual channels suggest that it has, at most, a marginal amplitude for decay into $\rho\rho\pi$.

The most recent revision of the meson spectroscopy table by the Particle Data Group⁽¹⁾ has relegated all reported bosons with a mass greater than $2 \text{ GeV}/c^2$ to the questionable category. This followed the failure of the recent missing mass spectrometer experiment of the Northeastern-Stony Brook collaboration⁽²⁾ to confirm the plethora of sharp states observed over a period of years by the CERN Boson Spectrometer group. Although the two sets of experiments are not directly comparable, it is clear that additional data is required in the higher mass regions ($> 2 \text{ GeV}/c^2$). Other extant evidence suggests that there exists in the mass region $2.1 - 2.4 \text{ GeV}/c^2$ (T region) at least two states of opposite G parity. Although there is some disparity in the reported masses and widths, both Kramer et al.⁽⁴⁾ using $13 \text{ GeV}/c \pi^+ p$ film and Cason et al.⁽⁵⁾ from an $11 \text{ GeV}/c \pi^-$ experiment observe dipion enhancements in the mass region of $\approx 2.2 \text{ GeV}/c^2$. Furthermore, from the results of a series of $\bar{p}p$ formation type experiments, Kalbfleisch et al.⁽⁶⁾ have suggested the existence of a (probably) isovector $pp\pi$ state in the same mass region. An earlier $\bar{p}p$ annihilation experiment of Alles-Borelli et al.⁽⁷⁾ found a T region enhancement in the $\pi^+ \pi^- \pi^0$ spectrum. It is apparent that these enhancements cannot be manifestations of the same state and since the resonance situation in the T region is not understood, we deem it appropriate to present our data bearing on the matter.

Our data derive from a 150,000 picture exposure of the 80 inch BNL deuterium bubble chamber to $7.87 \text{ GeV}/c \pi^+$ mesons. Since we report only on charge exchange π^+ -neutron reactions, often with more than a single neutral particle in the final state, we have included only events having a visible spectator proton. To minimize scanning

biases we have further required all events to have momentum transfers between the incident π^+ and outgoing boson system of less than $50 m_\pi^2$. With these restrictions each event corresponds to a $0.6 \pm .06 \mu\text{b}$ cross section.

Since the most extensive searches for higher mass bosons have been made utilizing missing mass spectrometers and since Miller⁽⁸⁾ was able to observe enhancements in both the T region and X region (≈ 2650 MeV) by analyzing a 13 GeV/c π^+p bubble chamber experiment in a pseudo-missing mass manner, we present in Fig. 1 similar data for our experiment. This histogram contains the mass spectrum for all events of the type, $\pi^+d \rightarrow p_g pX^0$, where X represents any bosonic state with four charged pions or less. Thus, this spectrum corresponds to that which would be observed by a 4π solid angle missing mass spectrometer gated to accept only charged particle exchange processes, excluding only events with more than four charged pions in the final state. Even though the statistics available in our study are meager by "mms" standards, the fact that no missing mass experiment is available using a deuterium target and that the corrections to the "raw" bubble chamber data are minimal would seem to warrant the presentation of this data. From Fig. 1 the only clear enhancements observed are in the f^0 , A_2 , $\rho(1670)$ and T regions. (The smooth curve is hand drawn background.) The maximum deviation from this curve in any bin or adjacent group of bins is 1.8 standard deviations except for the f, g, and T regions. The statistical significance of the enhancements in both the g and T regions is slightly greater than four standard deviations. Figures 2a and 2b show the effect on the missing mass spectrum of eliminating the patently even and odd G parity states, respectively, from the complete spectrum (final states with more than a single neutral

pion appear in both histograms). The most notable feature of this selection is the sharpening of the T region enhancement in the odd G parity final states where its statistical significance rises to about five standard deviations.

To investigate this enhancement in greater detail we unfold the missing mass spectrum into its various components in Fig. 3a-f. The reactions represented by these figures are :

(a) $\pi^+ d \rightarrow p_s p \pi^+ \pi^-$	(1515 events)
(b) $\pi^+ d \rightarrow p_s p \pi^+ \pi^- \pi^0$	(1929 events)
(c) $\pi^+ d \rightarrow p_s p \pi^+ \pi^+ \pi^-$	(400 events)
(d) $\pi^+ d \rightarrow p_s p \pi^+ \pi^+ \pi^- \pi^0$	(787 events)
(e) $\pi^+ d \rightarrow p_s p MM$	(835 events)
(f) $\pi^+ d \rightarrow p_s p \pi^+ \pi^- MM$	(3164 events)

where p_s refers to the slower final state proton and MM denotes a neutral missing mass greater than one π^0 . The most striking feature of these histograms is that all of the odd G parity states and those that contain odd G parity states (Fig. 3b, d, e, f) demonstrate enhancements in the T region ($2.1 - 2.4 \text{ GeV}/c^2$). In addition, we observe that the dipion spectrum (Fig. 2) besides showing strong ρ^0 and f^0 signals, exhibits production of both the g^0 and $S^0(1920)$ at approximately 3-1/2 standard deviation significance. This spectrum is quite similar, excluding the presence of the f^0 , to the $\pi^+ \pi^0$ spectrum observed by the ABC collaboration⁽⁹⁾ in an $8 \text{ GeV}/c \pi^+ p$ experiment. In particular, both experiments observe, at most, a marginal signal in the T region. Thus, we conclude that the T region enhancement observed in our experiment is either not related to the previously reported dipion T state or else that the latter state has in

its neutral channel dominant decay modes into purely neutrals or into $\pi^+ \pi^- (n\pi^0) (n \geq 1)$.

The appearance of a signal in the 5π spectrum suggests that we may be observing the $\rho^0 \rho^0 \pi^0$ state reported by Kalbfleisch et al. (6). However, the shaded area of this histogram (Fig. 6) which indicates the effect of a $\rho^0 \rho^0 \pi$ selection on our data is void of any marked signal in the T mass region. Furthermore, no signal is observed in the $\rho^\pm \pi^\pm \rho^0$ spectrum (not shown). We therefore conclude that there exists at least one enhancement in the T region ($2.1 - 2.4 \text{ GeV}/c^2$) which has a production cross section in $\pi^+ - n$ charge exchange interactions of $95 \pm 20 \mu\text{b}$. It decays primarily into $(\pi^+ \pi^- \text{MM})$, to a lesser extent into $\pi^+ \pi^+ \pi^- \pi^- \pi^0$, all neutrals, $\pi^+ \pi^- \pi^0$, and has no appreciable decay into $p\bar{p}$.

References

1. Particle Data Group, Physics Letters, April (1972).
2. Northeastern-Stony Brook Collaboration, summary by D. Garelick at Experimental Meson Spectroscopy Conference.
3. M. N. Focacci et al., Phys. Rev. Letters 17, 890 (1966).
B. Levrat et al., Phys. Letters 22, 714 (1966).
M. Chikovani, et al., Phys. Letters 22, 233 (1966).
4. S. L. Kramer, et al., Phys. Rev. Letters 25, 396 (1970).
5. C. Cason et al., Nuovo Cimento 62A, 755 (1969).
6. G. Kalbfleisch et al., Physics Letters B29, 259 (1969); Nuclear Physics B30, 466 (1971).
7. V. Alles-Borelli et al., Nuovo Cimento 50A, 775 (1967).
8. D. H. Miller, P. 457, Experimental Meson Spectroscopy, edited by C. Baltay and A. H. Rosenfeld, Columbia University Press, New York, 1970.
9. ABC Collaboration, Nuclear Physics B4, 501 (1968).

Figure Captions

1. Composite bosonic mass spectrum from 7.87 GeV/c π^+ -n charge exchange interactions, as described in the text.
2. (a) Bosonic mass (m_B) spectrum for the reaction $\pi^+ d \rightarrow p_s pB$, with even G parity states eliminated (so far as is possible).
 (b) m_B with odd G parity states eliminated (so far as is possible).
3. Bosonic spectra for the reactions:

(a) $\pi^+ d \rightarrow p_s p \pi^+ \pi^-$	(d) $\pi^+ d \rightarrow p_s p \pi^+ \pi^+ \pi^- \pi^- 0$
(b) $\pi^+ d \rightarrow p_s p \pi^+ \pi^- 0$	(e) $\pi^+ d \rightarrow p_s p MM$
(c) $\pi^+ d \rightarrow p_s p \pi^+ \pi^+ \pi^- \pi^-$	(f) $\pi^+ d \rightarrow p_s p \pi^+ \pi^- MM$

ORNL-DWG 72-7499

The Four Pion Decay of the f^0 Meson*

W. M. Bugg, G. T. Condo, and E. L. Hart

University of Tennessee, Knoxville, Tennessee 37916

H. O. Cohn and R. D. McCulloch

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

R. J. Endorf, C. P. Horne,[†] and M. M. Nussbaum

University of Cincinnati, Cincinnati, Ohio 45221

ABSTRACT

A search for the $\pi^+\pi^+\pi^-\pi^-$ decay mode of the $f^0(1260)$ has been made in 7.87 GeV/c π^+d interactions. We find no evidence for this decay. The ratio of this decay mode relative to the dipion decay mode of the f^0 is consistent with zero and less than 3.3% with 90% confidence.

*Research jointly sponsored by the U. S. Atomic Energy Commission under contract with Union Carbide Corporation and the University of Tennessee, U. T. Contract AT-1-3956, and the University of Cincinnati, Contract AT(11-1)-2090.

[†]Present address: Department of Physics, Florida State University, Tallahassee, Florida 32306.

There have recently been several reports of a small but statistically significant 4π decay mode of the f^0 . Ascoli *et al.*¹ obtained a corrected ratio for $F = \frac{f^0 \rightarrow \pi^+ \pi^+ \pi^- \pi^-}{f^0 \rightarrow \pi\pi}$ of $7 \pm 4\%$ from a 5.1 GeV/c $\pi^- p$ experiment, while Oh *et al.*² reported the ratio to be $7 \pm 2\%$ from a 7 GeV/c $\pi^- p$ experiment. On the other hand, the most recent results by Bardadin-Otwinowska *et al.*³ from a study of 8 GeV/c $\pi^+ p$ interactions, show little evidence for the four pion decay of the f^0 . They obtain a ratio $F = 2.2^{+4.5}_{-2.2}\%$, consistent with zero. The Meson Spectroscopy Table of the Particle Data Group⁴ gives a world average of $F = 6.1 \pm 1.5\%$. Our data presented below are in agreement with the null result of Bardadin-Otwinowska.³

The data derive from a 0.6 μb event exposure of the B.N.L. 80 inch deuterium bubble chamber exposed to a beam of 7.87 GeV/c π^+ mesons. Only events with a spectator proton identifiable on the scanning table have been selected. The channels relevant to the present work are

$$(a) \quad \pi^+ d \rightarrow p_s p \pi^+ \pi^- \quad (-t \leq 10 \text{ m}_\pi^2) \quad (963 \text{ events})$$

$$(b) \quad \pi^+ d \rightarrow p_s p \pi^+ \pi^- \pi^+ \pi^- \quad (-t \leq 10 \text{ m}_\pi^2) \quad (92 \text{ events})$$

where p_s denotes a visible spectator proton and $(-t \leq 10 \text{ m}_\pi^2)$ implies that only peripheral events have been selected for analysis. This peripherality requirement reduces the non-resonant background in the f^0 mass region. (In this paper the momentum transfer, $-t$, is always calculated between the incident π^+ and outgoing bosonic system.) Figure 1 presents the 2π and 4π mass spectra with these restrictions. While a large f^0 signal is visible ($\sigma \approx 120 \mu b$) in the $\pi^+ \pi^-$ spectrum, the existence of a signal in the 4π spectrum is dubious. Our results are consistent with a zero four pion branching ratio for the f^0 .

For the purpose of the present study, we have selected the f^0 mass region to be $1.18 \text{ GeV}/c^2 \leq m_{f^0} \leq 1.34 \text{ GeV}/c^2$. This choice seems prudent since the four pion spectrum is rapidly rising in the vicinity of $1.4 \text{ GeV}/c^2$ in a manner atypical of any type of phase space which we have been able to generate, but which could be indicative of ρ' production.⁵ A larger f^0 region would enhance the 4π contribution in an artificial way. Figure 2 exhibits the momentum transfer $(-t)$ distributions for the f^0 region for the 2π and 4π events. In the latter group, only 4 events are in the f^0 region, all with $(-t) \leq 10 m_\pi^2$. With such a small sample of events in the f^0 region of the 4π spectrum, it is difficult to assess a background subtraction. From an examination of Fig. 2b, it would appear that at least one of these events is background. To determine the number of $\pi^+\pi^-$ decays of the f^0 in the above mass and $(-t)$ regions, we note, from Fig. 2, that there is a maximum of 173 events of this type. Furthermore, we estimate from Fig. 1 that at least 70% of these are f^0 events. Isotopic spin conservation requires that the $\pi^0\pi^0$ decay be 1/3 of the total dipion f^0 decay (our data agree with this figure to within one standard deviation). Using these criteria,

$$F = \frac{f^0 \rightarrow 2\pi^+2\pi^-}{(f^0 \rightarrow \pi^+\pi^-) + (f^0 \rightarrow \pi^0\pi^0)} = 0.017 \begin{matrix} +0.010 \\ -0.017 \end{matrix}$$

Finally, we display in Fig. 3 the corresponding data available from a $3.29 \text{ GeV}/c$ π^+d experiment utilizing the 20 inch B.N.L. bubble chamber for which each event corresponded to a cross section of $1.33 \mu\text{b}$. Again there is no compelling evidence for any 4π decay of the f^0 and the branching ratio, F , is consistent with the above determination.

Our conclusion is that the ratio of the decay of the f^0 into 4 charged pions relative to its decay into 2 pions ($\pi^+\pi^-$ and $\pi^0\pi^0$) is consistent with zero and has an upper limit of 3.3% with 90% confidence.

We acknowledge with gratitude the help of the B.N.L. staff in obtaining the bubble chamber data.

REFERENCES

1. G. Ascoli et al., Phys. Rev. Lett. 21, 1712 (1968).
2. B. Y. Oh et al., Phys. Rev. D1, 2494 (1970).
3. M. Bardadin-Otwinowska et al., Phys. Rev. D4, 2711 (1971).
4. Particle Data Group, Physics Letters 38, 1 (1972).
5. G. Smadja et al., Proceedings of the Conference on Experimental Meson Spectroscopy, 1972; p. 349, American Institute of Physics, New York, 1972.

FIGURE CAPTIONS

- Fig. 1. a) Dipion mass spectrum from reaction, $\pi^+ d \rightarrow pp\pi^+\pi^-$ at 7.87 GeV/c,
with $(-t)_{\pi^+\pi^-} \leq 10 m_\pi^2$.
b) Four pion mass from reaction, $\pi^+ d \rightarrow pp\pi^+\pi^-\pi^+\pi^-$ at 7.87 GeV/c,
with $(-t)_{\pi^+4\pi^-} \leq 10 m_\pi^2$.

Fig. 2. Momentum transfer distributions for events in the mass region
(1.18 - 1.34) GeV/c² for:

- a) Dipion events.
b) Four pion events.

Fig. 3. For 3.29 GeV/c $\pi^+ d$ interactions:

- a) 4π mass spectrum for the $pp\pi^+\pi^+\pi^-\pi^-$ final state with
 $(-t)_{\pi,4\pi} \leq 10 m_\pi^2$.
b) 2π mass spectrum for the $pp\pi^+\pi^-$ final state with $(-t)_{\pi,4\pi} \leq 10 m_\pi^2$.
c) Momentum transfer distribution for 4π events in the f^0 region.
d) Momentum transfer distribution for 2π events in the f^0 region.

ORNL-DWG 72-8886

ORNL-DWG 72-8885

F163