STUDY OF THE R MESON PRODUCED IN 13 GeV/c π^+p INTERACTIONS*

G. Thompson, J. A. Gaidos, R. L. McIlwain, D. H. Miller,
T. A. Mulera, and R. B. Willmann

Purdue University, Physics Department, Lafayette, Indiana 47907

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.

ABSTRACT

The missing mass spectrum opposite the proton in a 750,000 picture exposure, 13 GeV/c π^+p bubble chamber experiment, is investigated in two and four pion channels for structures observed or denied by boson spectrometers at the same energy in the reaction $\pi^+p \rightarrow X^+p$.

In the four pion final state the R^+ enhancement is observed clearly and the possibility of multi-component mass structure is considered. Treating the phenomenon as one object, cross sections and branching ratios are derived for intermediate quasi two and three body decay modes ($\omega\pi$, $\rho\rho$, $A_2\pi$, $\rho\pi\pi$). The signals in the two pion state and for the neutral state produced opposite Δ^{++} (1231) are also presented and an elasticity is calculated.

*Work supported in part by the U.S. Atomic Energy Commission.

MASTER

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.

1. INTRODUCTION

Interest in the boson spectrum above $1 \text{ GeV}/c^2$ increased in 1965 when the CERN Missing Mass Spectrometer (CMS) Group reported seeing a series of new meson enhancements called the R, S, T, U [1]. The S, T, U were observed as narrow structures and the broad R enhancement ($1600 \sim 1750 \text{ MeV}/c^2$) was thought to be split into at least three parts designated R_1 , R_2 and R_3 . A subsequent experiment by a Northeastern-SUNY collaboration using the same technique [2] and also using incident π^- mesons failed to confirm the S, T, U enhancements with the reported widths and cross sections, and preferred to describe the R as one broad resonance centered at $1648 \text{ MeV}/c^2$, implying a mass scale shift of $43 \text{ MeV}/c^2$ below the CERN results. The data of this collaboration was also consistent with a wide S meson of $\Gamma = 133 \text{ MeV}/c^2$.

When the CERN Boson Spectrometer (CIBS) was used at Serpukhov in 1971 and also failed to see narrow S, T, U mesons [3] the results were reconciled by presuming an over estimate of cross sections by a factor ~ 4 in the original experiment [4], with no change in the statistical significance. These high statistics counter experiments have therefore given conflicting results and the situation regarding high mass mesons is unclear.

Many results have been published from bubble chamber production experiments concerning the R, S, T, U and the statistical significance of these results is slowly approaching that of the counter experiments.

This technique has many advantages since events with a proton recoil can be selected unambiguously as can particular decay modes of meson states. Such experiments have produced the only detailed knowledge we have of the R region.

The ρ meson decaying to two pions has been known and studied for several years. Analyses of the $\langle Y_n^{\ell} \rangle$ moments yield $J^P = 3^-$. The mass is commensurate

with the R ($\sim 1680 \text{ MeV}/c^2$) and it is quite wide [$\sim 160 \text{ MeV}/c^2$]. Bubble chamber experiments have also clearly observed a 4π enhancement in the R region sometimes called the $\rho(1710)$ but its identification as another decay mode of the g and the relative fractions of decay into pp , $\pi\pi$, πA_2 , etc. are not well determined.

In the $I = 1$ odd G parity system only the A_3 is known to exist and its interpretation as a resonance is still uncertain.

Statistically weaker are claims to observe several states in different decay modes in the R region although it does seem extremely difficult to fit all existing data with only the g and A_3 .

The data which is discussed in the following sections come from a 750,000 picture exposure of the SLAC 82" hydrogen bubble chamber to a $13 \text{ GeV}/c \pi^+$ beam. Previous results published from the first third of this film indicated that the g appeared to be narrow whereas the $R(\rightarrow 4\pi)$ was broad [6,7].

The two and four prong channels are now completely measured and in the present paper possible structure in, and decay modes of, the R region are investigated using the four prong one constraint topology. In addition, two pion spectra and production opposite the Δ^{++} (1231) are reexamined. Certain sections of this analysis are based on incomplete but unbiased, subsamples.

A subsequent paper will give detailed branching ratios and cross sections for the R^+ and R^0 decays including rare channels involving kaons.

2. A $13 \text{ GeV}/c \pi^+$ MISSING MASS EXPERIMENT WITH 4π STERADIAN ACCEPTANCE

In fig. 1 is shown a compilation for all two and four prong events of the missing mass above $1 \text{ GeV}/c^2$ observed opposite the proton. Events with six or more charged tracks were not measured for $3/4$ of the exposure and have been omitted. The six prong topology is, however, only $\sim 12\%$ total cross section and quoted decay modes of the high mass mesons into more than three charged particles are compatible with zero [1].

In order to eliminate ambiguous event interpretations, a cut P_{LAB} (proton) < 1.2 GeV/c has been imposed, and to improve the resolution fitted quantities have been used where there is one or no missing neutrals. However, the average resolution is still only 32 MeV/c^2 half width at half maximum in the 2 GeV/c^2 region. Final statistics are only slightly below present counter experiments and although this figure contains almost all t' values its resemblance to the published spectra of counter experiments [1,2] is striking. There is an identifiable A_2 region and then a slow rise to higher mass values interrupted by a broad shoulder in the R region, and a one standard deviation bump near the S.

To obtain a t' region similar to that which would result from a Jacobian peak measurement, the selection $0.1 \leq |t'| \leq 0.3 \text{ GeV}^2$ was imposed giving the shaded histogram. As may be seen, the R signal diminishes in significance considerably.

It is a conclusion from an analysis of this data that the t' dependence of the even G parity components in the 1.6 to 1.8 GeV/c^2 region is as steep or steeper than that of the $A_3(1650)$ ($\sim e^{-8t'}$) [8]. Spectrometer investigations, therefore, are likely to give erroneous results when analyzing broad structures in terms of a single resonance.

3. ANALYSIS OF THE DECAY MODES OF THE R

3.1 Channels used for the analysis

For the remainder of this paper the reactions used to study production of the even G parity system opposite a proton are:

$$\pi^+ p \rightarrow p(\pi^+ \pi^+ \pi^- \pi^0) \quad 1 \text{ constraint} \quad (1)$$

$$\pi^+ p \rightarrow p(\pi^+ \pi^0 \pi^0 \pi^0) \quad 0 \text{ constraints} \quad (2)$$

$$\pi^+ p \rightarrow p(\pi^+ \pi^0) \quad 1 \text{ constraint} \quad (3)$$

and in order to eliminate spurious reflections from the $\Delta^{++}(1231)$ a selection $M(\pi\pi_g^+) > 1.4 \text{ GeV}/c^2$ is imposed. Here, π_g^+ indicates that positive pion having the smaller longitudinal momentum in reaction (1).

Similarly, for production of even G parity mesons opposite a Δ^{++} a selection $1.12 \leq M(\pi\pi_g^+) \leq 1.32 \text{ GeV}/c^2$ is made to define the reactions

$$\pi^+ p \rightarrow \Delta^{++} \pi^+ \pi^- \quad 4 \text{ constraints} \quad (4)$$

$$\pi^+ p \rightarrow \Delta^{++} (\pi^+ \pi^- \pi^0 \pi^0) \quad 0 \text{ constraints} \quad (5)$$

3.2 Four pion decay modes

Fig. 2 displays the four pion spectrum from the reaction

$$\pi^+ p \rightarrow \pi\pi^+ \pi^+ \pi^- \pi^0 \quad (6)$$

selected as described to exclude Δ^{++} , the entire channel cross section is $1.23 \pm .06 \text{ mb}$ [9]. There is some production of Δ^0 and N^{*} 's but as these reflect smoothly at very high (4π) mass values and as they appear over a large background they have not been removed. A broad shoulder is present, clearly due to $B^+(1250)$ production and a sizeable enhancement appears in the $1.6 \sim 1.8 \text{ GeV}/c^2$ region with a somewhat spiky appearance. Fitting a single simple S wave Breit-Wigner plus background in this region results in $\sigma(K^+ \rightarrow \pi^+ \pi^+ \pi^- \pi^0) = 18.5 \pm 2.9 \mu\text{b}$.[†] Masses and widths derived for this and other fits are summarized in fig. 3.

The background for these fits is computed with the program FOWL [10] using a peripheral phase space and inserting the experimentally observed t' dependences between each of the secondary particles. No baryon resonances are included but the matrix element is amended slightly to give the proportions of the lower mass $A_2 \rightarrow \pi\pi$, and independent p production observed. In the generated events these are not correlated with any particular 4π

[†] Here and elsewhere in the paper cross sections are calculated by integrating the fitted Breit-Wigner over all available phase space.

mass region. This procedure gave a good agreement to all observed spectra even outside the domain of immediate interest and is considered to be a highly important technique for determining the effect of quasi two or three body decay cuts on the data.

The inset plot of fig. 2 shows the result of adding to the fitted background three components of the R meson with the maximum widths permitted by the CMS and the same mass spacing [1]. Cross sections are extrapolated from the published $d\sigma/dt$ and (1 charged/3 charged) ratio using an exponential slope of $\sim 6 \text{ (GeV/c)}^{-2}$. This value gives a minimum predicted signal but the variation with slope is small. In addition the cross section reduction factor 4 [4] has been used; the error on this number probably being big enough to swamp the other sources of uncertainty together with any P_{LAB} dependence. It is interesting to note that apart from a strong confirmation of the factor 4, this procedure also supports the Northeastern-SUNY result on an error in the CERN mass scale. The resulting χ^2 may be reduced from 154 to 74 by moving all components down by 35 MeV/c^2 and it is then comparable to the χ^2 of 70 for 70 degrees of freedom found from the simple (B meson + single R) fit.

Using similar cross section extrapolations from published Northeastern-SUNY results [2] and accepting an average CMS (1c/3c) ratio gives a predicted event count under a single R peak of 1060 ± 201 to be compared to the observed 541 events. The discrepancy can be accounted for by contamination of the Northeastern-SUNY data from the A_3 , which, at this energy, has more than twice the R cross section for decay into three charged particles [8]. The agreement of cross sections between this experiment and the amended CMS results but not with the Northeastern-SUNY results could be due to the different triggers used in the two experiments. The CMS experiment demanded at

least one charged secondary forward and could also measure the approximate charged multiplicity. It is possible that this helped to reduce the A_3 contribution to the R region. If this were so all the cross sections could be compatible although a positive confirmation of the internal structure as claimed by CMMS is still needed.

3.3 t' Dependence of the R meson production

In the R region the $(4\pi)^+$ differential cross section has a dependence $e^{At'}$ with $A = 7.3 \pm .3 \text{ (GeV/c)}^{-2}$ in the range $0 < |t'| < 0.5 \text{ (GeV/c)}^2$ as may be seen from fig. 4. With a subtraction of the background using equal width control bands the t' distribution becomes even sharper ($A \sim 10 \pm 2 \text{ (GeV/c)}^{-2}$). With bubble chamber statistics it is impossible to distinguish different slopes for the decay modes to be presented in the next sections. It is clear, however, that all of the observed signals are associated dominantly with low t , a region which has been inaccessible to spectrometers.

A cut $|t'| \leq .08 \text{ (GeV/c)}^2$ (shaded histogram of fig.2) sharpens the leading edge of the R and gives the enhancement a square appearance with a number of internal components which associate very well with the CMMS $R_1-R_2-R_3$ spacing, though it should again be noted that the mass resolution in this area is 32 MeV/c^2 . Slightly higher in the mass spectrum, there is exposed a suggestion of bumps which may be correlated with an S and T but which are of very low statistical significance.

3.4 The Intermediate Decay Mode $\omega\pi^+$

The final $(4\pi)^+$ state may come from several possible quasi two body states and the cleanest of these alternatives is $\omega\pi^+$ because of the

comparatively low background under the ω^+ and its narrow width, which for this section is defined as $0.74 \leq M(\pi^+\pi^-\pi^0) \leq 0.86 \text{ GeV}/c^2$.

A fit to the $\omega^+\pi^+$ spectrum produced opposite a proton is shown in fig. 5. There is a clear B signal and also an unmistakable decay from the R, fixing I^G for this component at least as 1^+ . At lower energies there is some dispute as to whether the $\omega\pi$ decay signal is seen [11,12] but it has been reported at energies as high as $18.5 \text{ GeV}/c$ [13]. Correcting for the small number of events in the ω tails, the branching ratio is derived to be

$$\frac{\sigma(R^+ \rightarrow \omega^+\pi^+)}{\sigma(R^+ \rightarrow \pi^+\pi^+\pi^-\pi^0)} = 33 \pm 7\%$$

The signal/noise ratio of 2.3/1 in this decay channel may be used to get a reliable angular decay distribution for the R. Contamination from double counting ω^0 events is less than 1%. In fig. 6a-d is shown the Jackson (θ) and Trieman-Yang (ϕ) angles of the bachelor π^+ in the t-channel 3π rest frame, and the polar (χ) and azimuthal (ψ) angles of the ω^0 decay plane normal in its helicity frame. The mass selection is $1.6 \leq M(4\pi) \leq 1.8 \text{ GeV}/c^2$ with control bands of $100 \text{ MeV}/c^2$ either side subtracted. As a function of mass there is a rapid variation in the $\cos \theta$ distribution, but the two side maxima and a central peak persist strongly up to $1.9 \text{ GeV}/c^2$.

The superimposed curves shown are the distribution to be expected from the decay of $J^P = 3^-$ state produced by one pion exchange (OPE). This mechanism would constrain J^P to be in the natural parity series, and the ± 1 ω helicity correlation $\sin^2 \chi \sin^2 \psi$ thus implied is consistent with the

[†] In the $\pi^+\pi^-\pi^0$ spectrum with two entries made per event the signal/noise ₂ at the ω peak is 2.2/1. The fitted full width of a Gaussian is $65 \text{ MeV}/c^2$.

data to a confidence level of 26%. OPE and $I = 1$ restrict the series to odd J . The 3^- state is preferred over the 1^- by a χ^2 of 8.0 to 29.1 for 9 degrees of freedom but is indistinguishable from the 5^- which has a χ^2 of 8.1.

3.5 The intermediate decay modes $\rho\rho$ and $A_2\pi$

The $\rho\rho$ coupling has been considered to be the strongest of the 4π final states. In a compilation of all available experiments the branching ratio $(\rho\rho)/(4\pi)$ has been quoted as 0.50 ± 0.10 , and for the positively charged state a 9 GeV/c experiment reported 0.70 ± 0.15 [12]. A recent measurement [13] for the R^- decay obtained 1.0 ± 0.25 . The major problem with this decay is that a large proportion of phase space at 4π masses in the R region falls within ρ mass cuts. This is illustrated by the behavior of the peripheral phase space background in the fit to this channel of fig. 7. Also, there is a large overlap of $\rho\rho$ and $A_2\pi$ channels. In fig. 8 is displayed the events which are classified as $A_2^0 \pi^+$. As the A_2 signals are very poor in the (3π) spectra the additional constraint of requiring an $A_2 \rightarrow \rho\pi$ decay has been imposed. The shaded histogram then shows events of this type but which cannot be simultaneously $\rho^+\rho^0$. For the purposes of this paper, $0.66 \leq M(2\pi) \leq 0.85$ GeV/c² and $1.24 \leq M(3\pi) \leq 1.36$ GeV/c² define ρ and A_2 respectively.

It is clear that the major portion of the R signal occurs in events which are simultaneous candidates for these channels. It is interesting that the overall square structure of the R signal in 4π does not occur in any of the decay channels.

In an attempt to discover whether the $\rho\rho$ decay mode is a genuine effect correlated with the R, scatter plots of $(\pi^+\pi^0)$ mass against $(\pi^+\pi^-)$

mass were prepared with two entries per event. The number of events expected in the $\rho^+\rho^0$ crossover may then be calculated using control bands assuming simple addition of ρ^0 and background components. The differences from the actual number of events, expressed as a percentage of that expected, is shown as a function of 4π mass in fig. 9a. Effects due to the non-uniformity of phase space in such a scatter plot may be reduced by repeating the same procedure using dipion masses squared as in fig. 9b. In both of these diagrams a p mass band of width $300 \text{ MeV}/c^2$ has been used but variation of this parameter was also incapable of producing a significant enhancement of $\rho\rho$ events.

Allowing for the R signal which would be included anyway in $\rho\rho$ mass cuts, a branching ratio may be derived of

$$\frac{\sigma(R^+ \rightarrow \rho^+\rho^0)}{\sigma(R^+ \rightarrow \pi^+\pi^+\pi^-\pi^0)} = 13 \pm 9\%$$

compatible with fig. 9.

In the almost indistinguishable channel for "genuine" $A_2\pi$ decay:

$$\frac{\sigma(R^+ \rightarrow A_2^0 \pi^+)}{\sigma(R^+ \rightarrow \pi^+\pi^+\pi^-\pi^0)} = 36 \pm 14\%$$

Caution should be exercised in the use of branching ratios quoted in this and other publications. As has been noted, large R signals may be obtained with the judicious use of mass cuts but large fractions of these signals may be accounted for by the 4π phase space selection they imply. The low ratios in this paper as compared to previous analyses result entirely from an effort to apply a correction for this effect. It should be emphasized that no clear A_2^0 signals are seen in the three pion spectra when the Δ^{++} is removed, so the branching ratio applies only for the mass

cut definition used. The problem of the ambiguity between $A_2\pi$ and $\rho\rho$ also remains intractable.

The spectrum of fig. 7 indicates that there is a possible $\rho^+\rho^0$ decay of an S meson. A Breit-Wigner fit gives the parameters

$$M(S) = 1898 \pm 18 \text{ MeV}/c^2 \quad \Gamma(S) = 108 \pm \begin{smallmatrix} 41 \\ 27 \end{smallmatrix} \text{ MeV}/c^2$$

i.e. again $30 \text{ MeV}/c^2$ less massive than the CMS result. Although the width is large it is not clear whether this is the same phenomenon observed $45 \text{ MeV}/c^2$ higher by Northeastern-SUNY [2]. Fig. 9 fails to give any firm denial that the appearance of this signal in $\rho^+\rho^0$ is anything other than fortuitous.

3.6 The intermediate decay mode $\rho\pi\pi$

Both of the preceding states are subsets of the $\rho\pi\pi$ mode so it is possible that the decay is dominated by this quasi-three body state. To test this hypothesis the size of the ρ signal was measured as a function of 4π mass, by selecting a $100 \text{ MeV}/c^2$ band around $765 \text{ MeV}/c^2$ and using $50 \text{ MeV}/c^2$ bands either side to estimate the background. The percentage extra ρ events are then shown for the three possible $\rho\pi\pi$ decay modes in fig. 10. Most answers are positive, but there is no evidence for a particular enhancement in the R region, although, again, an extra one standard deviation ρ signal ($\sim 20\%$) could not be ruled out. This, however, could still be equivalent to a high branching ratio. The strongest statement which can be made about this data, and any other existing data, is that the $\rho\pi\pi$ branching ratio is probably $\lesssim 40\%$ and is made up of almost indistinguishable $\rho\rho$ and $A_2\pi$ subsets.

It is interesting to note the significantly smaller signal for $\rho^-\pi^+\pi^+$, since, if $A_2\pi$ dominated, the three $\rho\pi\pi$ states should be equal.

3.7 The intermediate decay mode $\eta\pi$

Using as definition $M(\eta) = 0.52 < M(3\pi)^0 < 0.58 \text{ GeV}/c^2$, the $\eta\pi$ mass spectrum is shown in fig. 11. Apart from a strong A_2 signal there is no structure whatever in the $\eta\pi$ histogram and this gives an upper limit of

$$\frac{\sigma(R^+ \rightarrow \pi(\eta(\pi^+\pi^-\pi^0)))}{\sigma(R^+ \rightarrow (\pi^+\pi^-\pi^+\pi^0))} < 2\%$$

3.8 One Charged Particle Decay Modes

A remaining possibility for 4π decay is the channel [14]

$$\pi^+p \rightarrow p\pi^+ (\pi\pi) \quad (2)$$

where the missing mass is assumed to consist of $\pi^0\pi^0\pi^0$. In the spectrum of $(\pi^+\pi\pi)$ there will be a great deal of contamination from the channel $\pi^+p \rightarrow pA_3^+$, $A_3^+ \rightarrow \pi^0\pi^0\pi^+$ but advantage may be taken of the neutral dipion system forming an f^0 and the remaining π^+ being generally slow. The cut $P_{\text{LAB}}(\pi^+) < 2 \text{ GeV}/c$ removes an f^0 signal in the $(\pi\pi)$ and hence presumably also all of the A_3 . This procedure has been checked in the corresponding four constraint channel where $f^0 \rightarrow \pi^+\pi^-$ and the isotopic spin relationships also are consistent.

After this treatment and the exclusion of Δ^{++} events the resulting spectrum may be seen in fig. 12 where a $|t'| < 0.15 \text{ GeV}^2$ cut has also been imposed to enhance the signal. The final enhancement is difficult to analyze because of the large background but the signal does indicate a significant non pp decay of the R.

3.9 Two Pion Decay

Using the reaction [14]

$$\pi^+p \rightarrow p\pi^+\pi^0 \quad (3)$$

the $(2\pi)^+$ state produced opposite the proton has the mass spectrum shown in fig. 13. Again the R region has a spiky appearance but the most prominent

structure fits a Breit-Wigner with a mass of $1632 \text{ MeV}/c^2$, an intermediate value between the R_1 and R_2 of the $(4\pi)^+$ spectrum.

If the $(2\pi)^+$ signal is fitted with the same single R parameters discovered for the $(\omega^0 \pi^+)$ spectrum the cross section of $1.5 \pm 1.0 \mu\text{b}$ gives an elasticity

$$\eta = \frac{\sigma(R^+ \rightarrow \pi^+ \pi^0)}{\sigma(4\pi)^+ + \sigma(2\pi)^+} = .08 \pm .05$$

under the assumption of only one object. This value is, however, subject to considerable error since if the mass and width parameters are left free the resulting cross section is $3.9 \pm .8 \mu\text{b}$ giving $\eta = .18 \pm .04$. In any case the elasticity is much smaller than other published values [12].

It should be noted that the channel cross section of reaction (3) for this experiment $0.38 \pm .07 \text{ mb}$ is also below that derived for neighboring experiments.

4. THE PRODUCTION OF THE R OPPOSITE THE $\Delta^{++}(1231)$

The suggestion of pion exchange implies that the g or R meson should also be observed in its neutral state opposite the $\Delta^{++}(1231)$. In the four pion decay mode this implies a zero constraint fit but for two pion decay the channel has four constraints.

The neutral two pion spectrum for the reaction

$$\pi^+ p \rightarrow \Delta^{++}(1231) \pi^+ \pi^- \quad (4)$$

is shown in fig. 14. When fitted to a single Breit-Wigner the parameters derived are $M(R) = 1683 \pm 15 \text{ MeV}/c^2$ $\Gamma(R) = 151 \pm 50 \text{ MeV}/c^2$ and cross section $10.8 \pm 1.2 \mu\text{b}$.

The spin-parity of a neutral object, with a mass around $1700 \text{ MeV}/c^2$, decaying into two pions has been determined to be 3^- [5]. It would seem natural to associate this with both the observed ω decay mode and this

two pion mode but the large background on which the 2π signals are situated precludes a meaningful Legendre polynomial decomposition.

The $(\pi^+\pi^-MM)$ spectrum opposite the Δ^{++} in the four prong zero constraint channel is shown in fig. 15a. In fig. 15b is displayed the result of making a cut of $0.4 < M(\pi^+\pi^-) < 0.6 \text{ GeV}/c^2$ which should enhance any decay to $\omega^0\pi^0$. Both have a shaded histogram of events with $|t'| < 0.1 (\text{GeV}/c)^2$. It is known that the mass resolution in this channel is very poor and it is possible that some events have been lost to the 1 constraint channel, so such events with $\chi^2 > 5.4$ and $MM > (2\pi^0)$, have been included in fig. 14. A signal is evident in the R region and it would seem that it is associated with low $|t'|$ and has a possible ω decay.

5. SUMMARY AND CONCLUSION

It has been determined that the present high statistics bubble chamber experiment could be consistent with the original claim for structure in the R region [1], accepting a factor ~ 4 over-estimate of cross section [4] and a mass scale shift of $35 \text{ MeV}/c^2$. Cross section discrepancies in other spectrometer investigations [2] are probably due to the odd G parity A_2 contaminating their data.

A single broad R is also compatible with the data and using this assumption some 1/3 of the decay is to the $\omega^0\pi^+$ final state. Angular distributions suggest a 3^- or 5^- state produced with a sharp t' dependence, compatible with one pion exchange. The $p^+\rho^0$ signal, previously considered to be the dominant decay mode is probably an effect of the rapidly rising phase space at this mass. The $A_2\pi$ mode could account for a further 1/3 of the decay but it is indistinguishable from pp . There is no strong evidence for any other quasi two or three body components.

A signal in the R region is also seen in the $(\pi^+ \pi^+)$ and $(\pi^+ \pi^0)$ spectra in the two prong topologies and the neutral (2π) and (4π) spectra produced opposite Δ^{++} (1231) show evidence for the same phenomena. The fraction of R decay into two pions appears to be different from values quoted at lower energies [12].

Overall it is easier to fit the data with more than one state but it is still possible to force consistency with a single broad resonance.

REFERENCES

- [1] B. Levrat et al., Phys. Letters 22, (1966) 714.
M. N. Focacci et al., Phys. Rev. Letters 17, (1966) 890.
- [2] D. Bowen et al., Phys. Rev. Letters 29, (1972) 890.
D. Bowen et al., Phys. Rev. Letters 30, (1973) 333.
- [3] Y. M. Antipov et al., Phys. Letters 40, (1972) 147.
- [4] W. Kienzle, Phys. Rev. D 7, (1973) 3520.

This reduction factor applies to the CIBS S,T,U, run at 12 GeV/c.
The R cross sections were derived from runs at 7 and 12 GeV/c.
If the published values are not to be decreased by this factor 4,
there is still disagreement between this experiment and CIBS.
- [5] G. Grayer et al., Phys. Letters 35B, (1971) 610.
- [6] S. L. Kramer et al., Particles and Nuclei 1, (1970) 131.
- [7] S. L. Kramer et al., Phys. Rev. Letters 25, (1970) 396.
- [8] G. Thompson et al., Purdue University Preprint submitted to Nuclear Physics B.
- [9] T. A. Mulera, Purdue University Thesis. Details of the 4 prong event processing appear here.
- [10] F. James. CERN program Library No. W505.
- [11] T. F. Johnston et al., Phys. Rev. Letters 20, (1968) 1414.
- [12] J. Bartsch et al., Nucl. Phys. B22, (1970) 109. This paper gives an excellent compilation of the g-meson prior to 1970.
- [13] N. M. Cason et al., Phys. Rev. 7, (1973) 1971.
- [14] S. L. Kramer, Purdue University Thesis. Details of 2 prong event processing appear here.

FIGURES

- [1] Missing mass spectrum observed opposite a proton with P_{LAB} (proton) $< 1.2 \text{ GeV}/c$. The shaded histogram has the selection $0.1 \leq |t'_{p-p}| \leq 0.3 \text{ GeV}^2$.
- [2] Effective mass $\pi^+\pi^+\pi^-\pi^0$ from reaction (1) cut to exclude Δ^{++} events. The shaded histogram has the cut $|t'_{pp}| < 0.08 \text{ GeV}^2$. The inset shows this data with the prediction of QMMS [1] in the R region. The smooth curves indicate Monte-Carlo generated background and superimposed Breit-Wigners.
- [3] Summary of the masses and widths obtained by Breit-Wigner fits to partial decay modes. In the diagram the horizontal line represents the fitted width.
- [4] Differential cross section of $(4\pi)^+$ mass interval $1.6 < M(4\pi) < 1.8 \text{ GeV}/c^2$. The lower points and line show the results of subtracting off equal mass control bands.
- [5] Mass spectrum of $\omega^0\pi^+$ with fitted Breit-Wigners in the B and R regions.
- [6] Decay angular distributions in the region $1.60 \leq M(\omega^0\pi^+) \leq 1.80 \text{ GeV}/c^2$ with background subtraction. (a) Jackson angle (θ) and (b) Trieman-Yang (ϕ) angle in the t-channel frame. (c) Polar (χ) and (d) the azimuthal (ψ) angle of the ω^0 decay plane normal in its helicity frame. The superimposed curves give the angular distributions expected from the decay of a 3^- state produced by one pion exchange.

- [7] Mass spectrum of $\rho^0 \rho^+$ with fitted Breit-Wigners in the R and S regions. See text for definition of ρ mass.
- [8] Mass spectrum of $A_2^0 \pi^0$ with $A_2 \rightarrow \rho \pi$. See text for definition of A_2 mass. The shaded histogram shows $A_2 \pi$ events which cannot be simultaneously $\rho \rho$.
- [9] Percentage of extra events observed in the $\rho \rho$ crossover region of $(\pi^+ \pi^0)$ vs. $(\pi^+ \pi^-)$ scatter plots, above expected number.
(a) using dipion masses (b) using dipion masses squared.
- [10] Percentage ρ signal in three possible decay modes of $\rho \pi^0$ as a function of $M_{\pi^+ \pi^+ \pi^- \pi^0}$, found by subtracting equal width control bands.
- [11] $\eta \pi^+$ mass spectrum. See text for definition of resonance masses.
- [12] The mass spectrum of $(\pi^+ \pi^0)$ from reaction (2) where Δ^{++} events are excluded and in addition $(\pi^0) > M(2\pi^0)$, $P_{LAB}(\pi^+) > 2 \text{ GeV}/c$. In the shaded histogram $|t'| < 0.15 (\text{GeV}/c)^2$.
- [13] The mass spectrum of $(\pi^+ \pi^0)$ from reaction (3), Δ^{++} excluded. In the shaded histogram $|t'| < 0.10 (\text{GeV}/c)^2$.
- [14] The mass spectrum of $(\pi^+ \pi^-)$ from reaction (4). In the shaded histogram $|t'| < 0.10 (\text{GeV}/c)^2$.
- [15] (a) The mass spectrum of $(\pi^+ \pi^- \pi^0)$ from the reaction $\pi^+ p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^0$.
(b) As above, but with the "pseudo- ω " cut $0.4 \leq M(\pi^+ \pi^-) \leq 0.6 \text{ GeV}/c^2$.
In both cases the shaded histogram has $|t'| < 0.10 (\text{GeV}/c)^2$.

Experiment - Channel	Mass	M (MeV/c ²)	Γ (MeV/c ²)
CERN MMS GROUP $\pi^- p \rightarrow x^- p$		1632 ± 15 1700 ± 15 1748 ± 15	0 < Γ ≤ 21 0 < Γ ≤ 30 0 < Γ ≤ 38
STONYBROOK-NORTH-EASTERN $\pi^- p \rightarrow x^- p$		1648 ± 7	139 ± 31
THIS EXPERIMENT	1.6 1.7 1.8 1.9		
$p(\pi^+ \pi^+ \pi^- \pi^0)$		1670 ± 10	106 ± 25
$p(\pi^+ \pi^+ \pi^- \pi^0)$ $ t' < 0.15(\text{GeV})^2$		1593 ± 10 1684 ± 10	10 ± 10 109 ± 30
$p(\omega^0 \pi^+)$		1686 ± 9	89 ± 25
$p(A_2^{\frac{3}{2}} \pi^2)$		1682 ± 11	128 ± 27
$p(\rho^0 \rho^+)$		1671 ± 9	127 ± 35
$p(\pi^+ \text{MM})$		1724 ± 14	86 ± 38
$p(\pi^+ \pi^0)$		1632 ± 5	42 ± 20
$\Delta^{++}(\pi^+ \pi^-)$		1683 ± 15	151 ± 50