INTERACTIONS OF PIONS, NUCLEONS AND ANTINUCLEONS

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This is not a report of the work on the subject presented at this Conference. There have been three parallel sessions where a good fraction of approximately 60 papers submitted has been presented and discussed. I have decided to discuss only one topic, i.e. the problem of the multipion systems, and even then to confine myself to the discussion of the few structures which appear to be well established. I apologize for such a drastic selection criterion and also for the way I am going to present some results; but I thought this was the only suitable way to leave a physicist not working in the specific field with something in his mind after the talk.

MULTIPION SYSTEM

The most important achievement in strong interactions since the last Rochester Conference is the discovery of the so-called multipion systems or pionic isobars. The discovery represents also the great success of the theoreticians, who called in advance for objects of this kind in order to understand the form factors of the nucleon [1]. Three of these objects have been definitely established, in the sense that they have been observed in different processes and some of their properties have been measured. In addition there are something like a dozen more peaks in the mass spectra of multipion systems, among which there may be some more interesting objects, but at present it is almost impossible to say which are going to survive.

Let us start with the 3 mentioned firmly established objects, namely ω, η and ρ. They appeared first as peaks in 3π and 2π mass spectra and they seem to carry well defined quantum numbers. The question whether to call them particles or resonances is very difficult to answer, at least for me, and it looks better to " pass the buck " to the theoretician.

But for the simple mind of the experimentalist the ω and especially the η look very much like particles, with unique quantum number assignments, essentially because of their small width. The so-called ρ peak, however, has the characteristics of a resonance in the dipion system, because it corresponds to a situation in which one partial wave becomes dominant among the others, its phase shift passing through 90°. In other words, if in the analysis of some processes I have to think in terms of particles, I will be much more confident of my approximation for ω and η than for ρ.

ω This object has been discovered in the analysis of proton-antiproton annihilation by Maglic *et al.* [2]. Looking at the mass distribution of the triplets $(\pi^+\pi^-\pi^0)$ among the annihilation processes in 5 pions $(2\pi^+2\pi^-\pi^0)$, a very narrow peak above background has been detected at a mass value of 785 MeV and with a width comparable with the experimental resolution (Fig. 1). The absence of any effect in other charge configurations of pion triplets $(\pi^\pm\pi^+\pi^-)$ has led to the assignment of isotopic spin $I = 0$. This finding was soon confirmed by other experimenters (Fig. 2) [3].

It is possible to determine spin and parity by studying the dynamics of the decay into 3 pions. As is well known there is a simple kinematical relation between the squares of the masses of the 3 pairs of pions in question, namely

$$M^2_{\pi^+\pi^-} + M^2_{\pi^-\pi^0} + M^2_{\pi^+\pi^0} = M^2_\omega - 3\mu^2$$

If one makes a 2 dimensional plot (the " Dalitz " plot) in any of the two square masses, the area covered corresponds to a uniform phase space volume. A particular feature in the population density of phase space gives information on the transition matrix element (Fig. 3a). Experimental results indicate a spin and parity assignment of 1^- [2].

Lastly comes the question of the so-called isotopic invariance or G-parity [4]. Any system of pions depending on whether the number of pions is even or odd, carries a special quantum number called G-parity

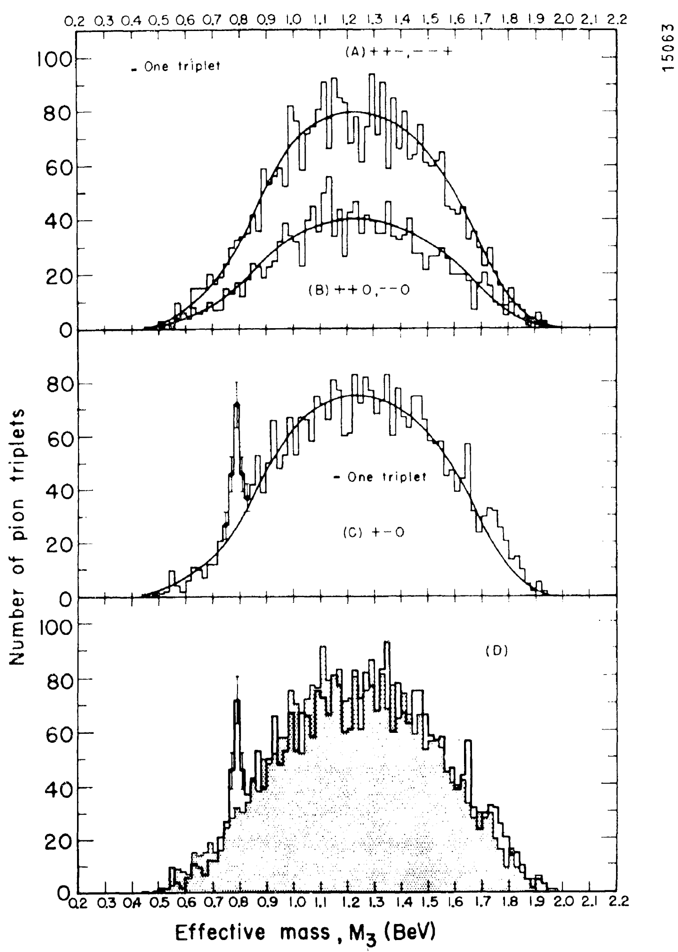


Fig. 1 First evidence for ω production in $\bar{p}+p \rightarrow 2\pi^+ + 2\pi^- + \pi^0$ in different charge configurations [12]).

with eigenvalue $+1$ and -1 respectively. This quantum number for a neutral system of pions, in which we are interested here, is related to the better known quantum number C (charge conjugation) by the relation $G = C(-1)^I$, where I is the isospin of the multipion system. If the I-spin is conserved in the ω decay, we can assign to the ω particle the quantum number $G = -1$, $C = -1$.

It was indeed found that the 3π decay is the dominant mode for the ω and so the G and C parity are fixed. The ω came to this conference clothed in all its quantum numbers

$$(J, P, G, I) = (1, -1, -1, 0) = 1_0^{--}$$

and here these numbers have received further strong support.

The mass of ω has been consistently found by everybody to be about 790 MeV with very small spread; also the width has been confirmed to be small, since everyone has found a width consistent with his own experimental resolution (in the more favourable cases this is smaller than 12 MeV). You can see in Figs. 3, 4, 5, 6 the present situation of its spin and parity assignment based on a world wide collection of data.

It is recognized by everybody that the dominant decay mode is $\omega \rightarrow \pi^+ + \pi^- + \pi^0$; now comes the more sophisticated experimental problem to establish the branching ratios for the other decay modes. All those modes occur through violation of G parity, because the only other 3π mode, $\omega \rightarrow 3\pi^0$, is strictly forbidden

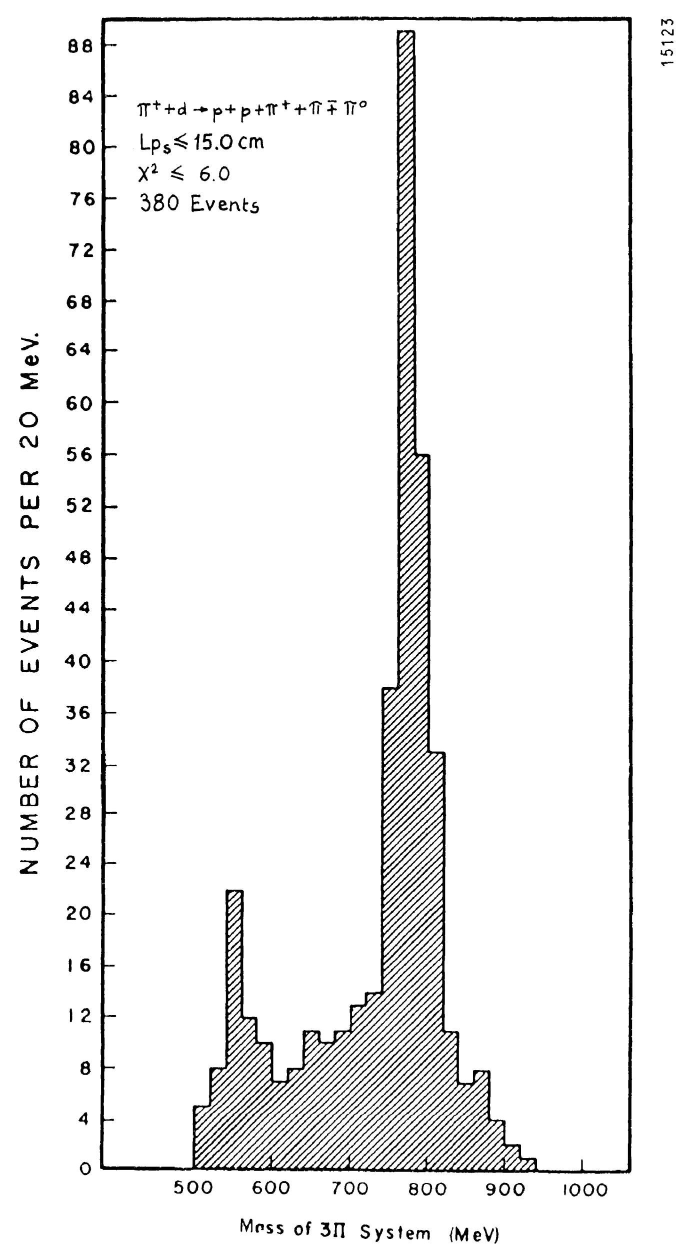


Fig. 2 Further evidence for ω production in $\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + \pi^0$, showing also evidence for η production [3]).

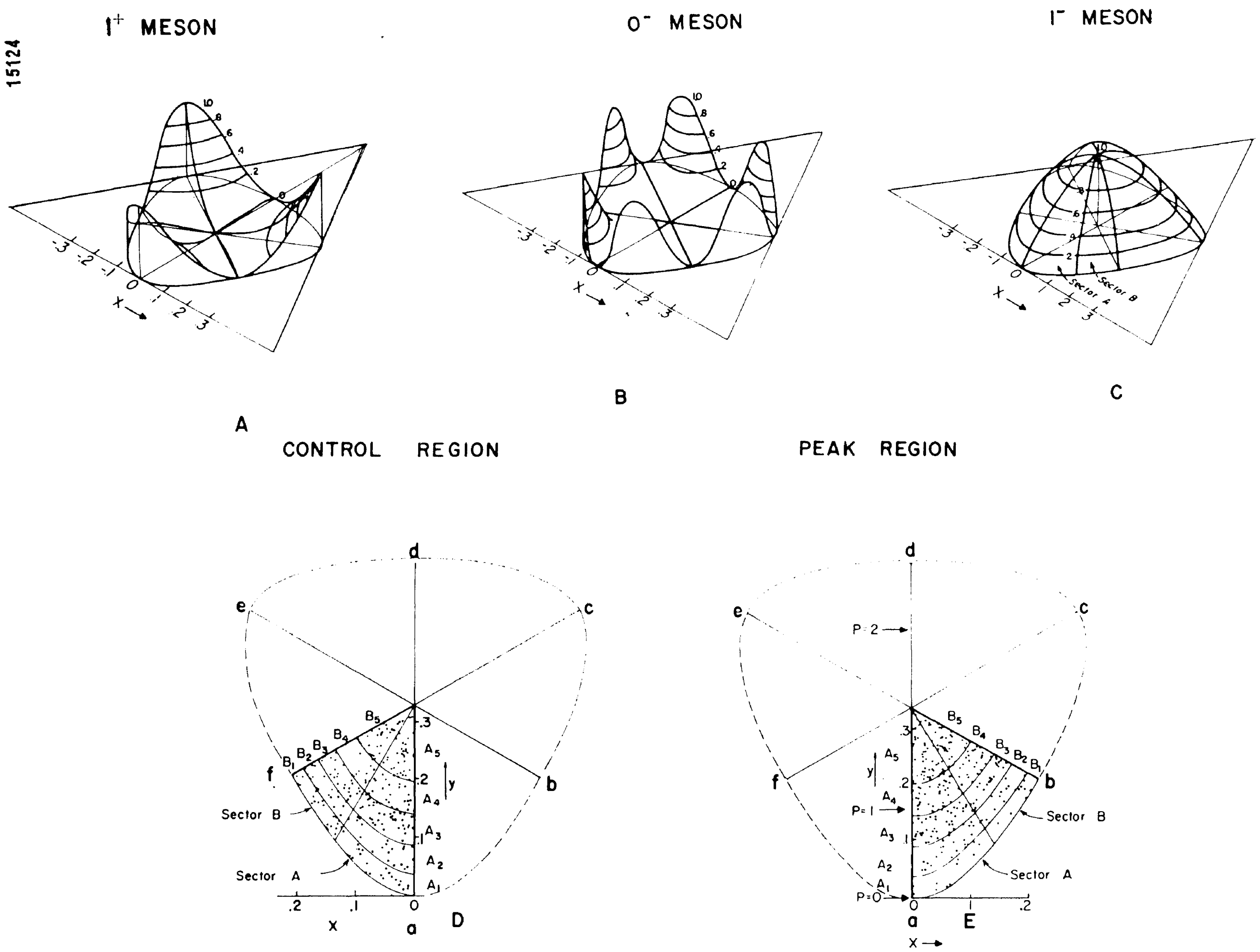


Fig. 3 a Dalitz plot for ω decay; 1100 point including about 375 background events [14].

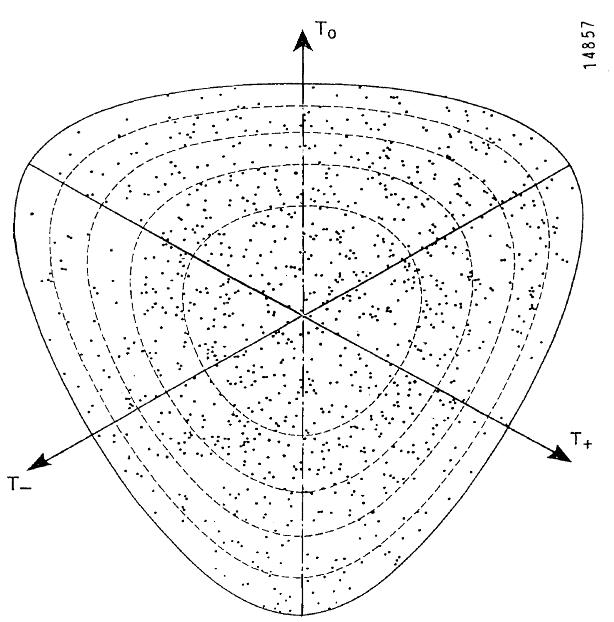


Fig. 3 b Three-dimensional visualisation of Dalitz-Stevenson plot for the ω decay [2].

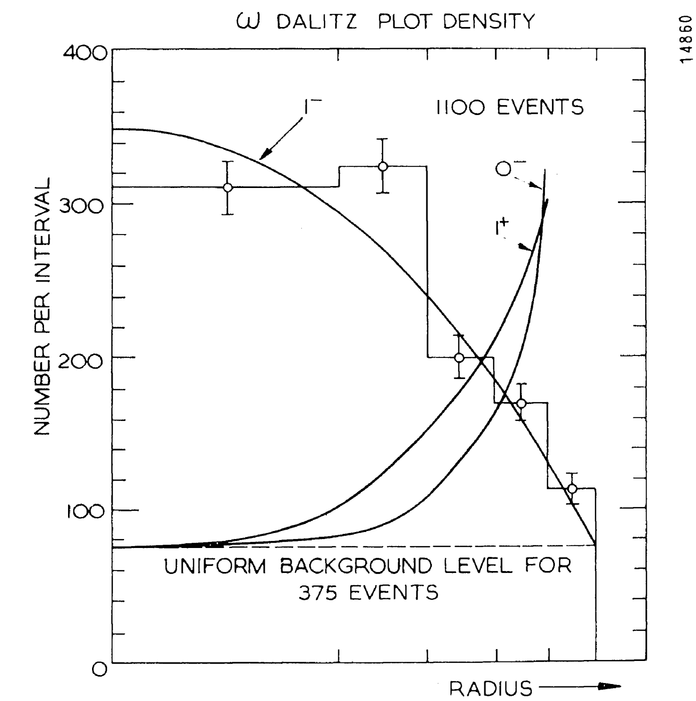


Fig. 4 Dalitz plot density (Stevenson plot) for ω decay, from Fig. 3 a. Predictions for different spin and parity assignments are shown. Data exclude 1^+ and 0^-.

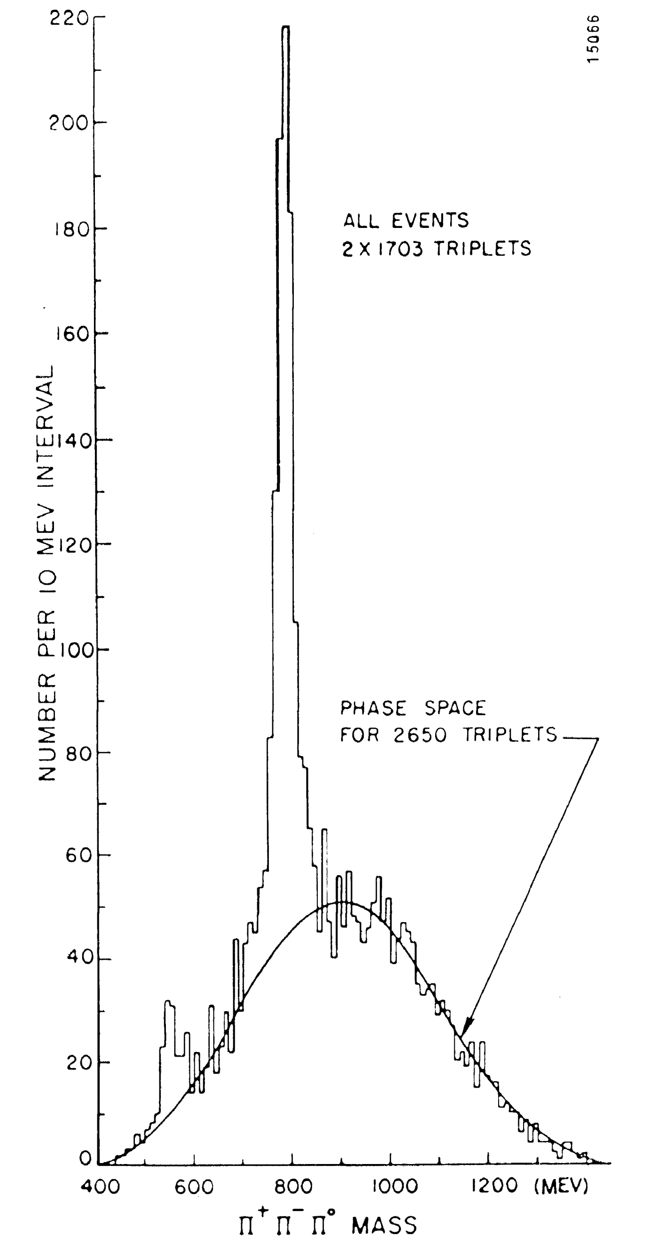


Fig. 5 Recent evidence for ω production in the $\pi^+\pi^-\pi^0$ mass spectrum from $\pi^+ + p \to \pi^+ + p + \pi^+ + \pi^- + \pi^0$; shows enhanced production if the phase space is more restricted [14].

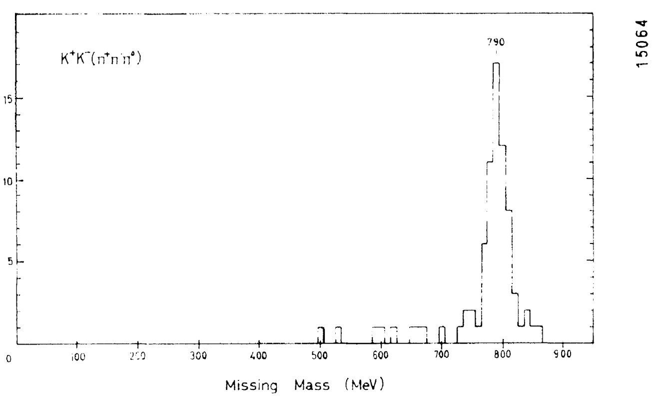
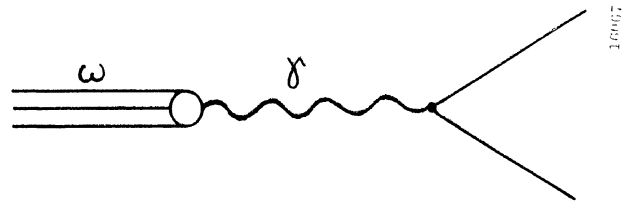


Fig. 6 Evidence for ω production in $\bar{p} + p \to K^+K^-(\pi^+\pi^-\pi^0)$ events (at rest) [20].

by C. The electromagnetic decays of the ω which violate G parity, were estimated with some particular models [5] which are mainly based on the following two arguments. Firstly if you assume that the ω can be coupled with a photon, a fact which is essential if one believes that the ω has something to do with form factors, processes occur like:



But for this very simple process one expects a very small branching ratio $\sim 1\%$. Secondly the ρ meson can act as an intermediary for two reasons, i.e. through a $(\omega\pi\rho)$ coupling and, if also the ρ has to do with form factors, through the coupling of the ρ with a photon. In this way one expects more contribution to the 2π mode and the $\omega \to \pi^0 + \gamma$ decay can also be calculated. The coming into play of ρ^0 could enhance in particular the 2π decay, owing to the very peculiar fact that the mass of ρ^0 and ω are very close, or it is better to say, the ω is in the region of the ρ^0 peak.

The contributions to this conference on the neutral decay mode of the ω which quite probably consist in the mode $\pi^0 + \gamma$, are summarized in Table I.

The problem of the branching ratio $\omega \to 2\pi$ is not in as good a shape as the other for the reason that if one really wants to see this mode of decay directly one has to look inside the broad peak of the ρ^0 meson, at least in the processes which do not discriminate against $I = 1$ multipion production. And as it has been recently said, with good humour, it is like the search for a needle in a haystack [6]. People who have searched for this kind of direct evidence, place a very low upper limit ($\sim$few per cent) on this branching ratio. With a more indirect approach, people who base this identification on the strong perturbation of the behaviour of ρ^0 in comparison with $\rho^\pm$, estimate a much greater fraction—of the order of 10-20 %.

Due to the difficulty of the first approach and to the uncertainty of the second one it is impossible to draw any conclusion and we had better leave this to be answered at the next conference.

η Shortly after the discovery of the ω particle, Pevsner *et al.* [3] noticed the presence of an object of mass

TABLE I

Authors	Process	$\frac{\text{No. of neutral decays}}{\text{No. of charged decays}}$ [in %]
Pevsner *et al.*[3]	$\pi^+ + d \rightarrow p + p + \omega$	6 ± 6
Alff *et al.*[14]	$\pi^+ + p \rightarrow N^* + \omega$	16 ± 6
Armenteros *et al.*[20]	$p + \bar{p} \rightarrow K\bar{K} + \omega$	21 ± 7.5
	$K^- + p \rightarrow \omega + \Lambda^0$	25 ± 10

around 550 MeV, decaying into a 3π system, while studying the reaction, already mentioned,

$$\pi^+ + d \rightarrow p + p + (\pi^+ \pi^- \pi^0)$$

which also confirmed the existence of the ω (see Fig. 2). Confirmation of the η soon came from the analysis of the reaction $K^- + p \rightarrow \Lambda^0 + (\pi^+ \pi^- \pi^0)$ just above the threshold for mass 550 MeV by Bastien *et al.* [7]. In addition, looking at the missing mass distribution in the configuration (Fig. 7)

$$K^- + p \rightarrow \Lambda^0 + (\text{neutrals})$$

they were able to observe the same structure also when it decays into neutral particles, giving as a ratio of the charged mode to the neutral ones, 0.33 ± 0.11. The possible charged counterpart ($\eta^\pm$) of this object was searched for [8] with a negative result leading to an isotopic spin assignment of $I = 0$, as for the ω.

Limited statistics, due to the low yield of the η in general and of the charged decay ($\pi^+ \pi^- \pi^0$) configuration in particular, leave the situation of the η, in what concerns the assignment of other quantum numbers, quite unclear despite the fact that arguments of the kind I am going to present in a moment led Bastien *et al.* immediately towards the solution which is now generally accepted. The idea that η-decay into $\pi^+ \pi^- \pi^0$ is not allowed by isospin conservation but proceeds via violation of G parity was favoured immediately for 3 main reasons:

(1) the large proportion of neutral decay in contrast with that in the case of the ω;

(2) the general better consistency of the Dalitz plot with uniformity;

(3) the lack of observation of the process $\rho \rightarrow \eta + \pi$.

This last process can most reasonably be inhibited only by conservation of G parity because of the opposite G parity of ρ (allowed decay into 2π) and π, positive G parity for η [9] is then suggested. So the η particle came to this conference well established in that which concerns its existence, isospin assignment, mass and small width and with a tentative quantum number assignment of 0_0^{-+}. At this conference clear peaks for η in the same position have been reported as a result of different experiments, of which I will present one example (Fig. 8). There are now avail-

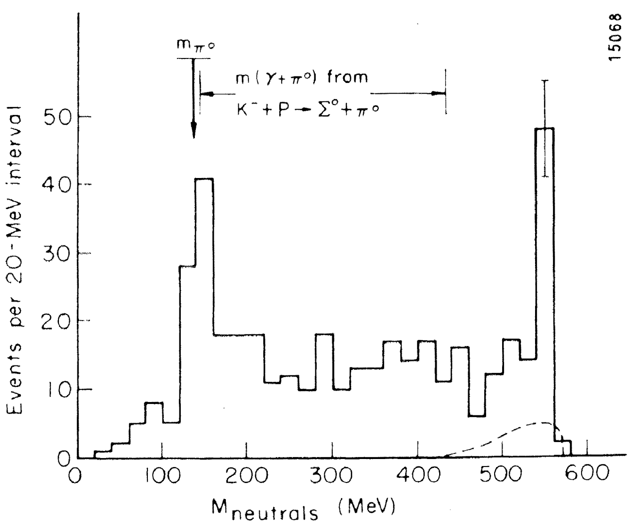


Fig. 7 Missing mass spectrum for 408 events from $K^- + p \rightarrow \Lambda + (\text{neutrals})$ at $p_K = 760$ MeV/c showing evidence for neutral decay mode of the η [7].

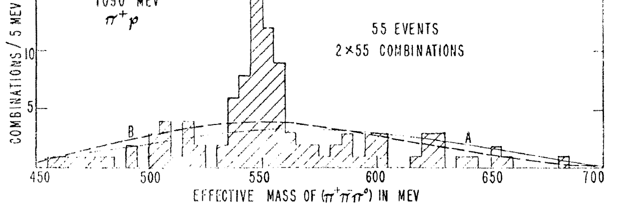


Fig. 8 Evidence for η production in $\pi^+ + p \rightarrow \pi^+ + p + \pi^+ + \pi^- + \pi^0$ [12a].

able in the world a few hundred η suitable for analysis and a collection of most of them is presented in Fig. 9. The events are uniformly distributed over the allowed area, as can be seen also from the analysis of the radial density shown in Fig. 10. Some non-uniformities present in previous plots with limited statistics have almost completely disappeared. The observation of the uniform distribution in the plot alone is sufficient to assign uniquely the set of 0^{-+} quantum numbers, but for the beauty of the argument let us see how this came out.

Let us start by making the two hypotheses on the G parity.

G = C = —1. In this case as in the case of ω, decay into $(\pi^+\pi^-\pi^0)$ is allowed and decay into $3\pi^0$ forbidden; there will be a first problem in explaining by means of violation of G the large yield of neutrals. In addition, the lowest spin and parity state which remain are 0^-, 1^-, 1^+ and none of these gives an uniform distribution. So $G = -1$ is ruled out.

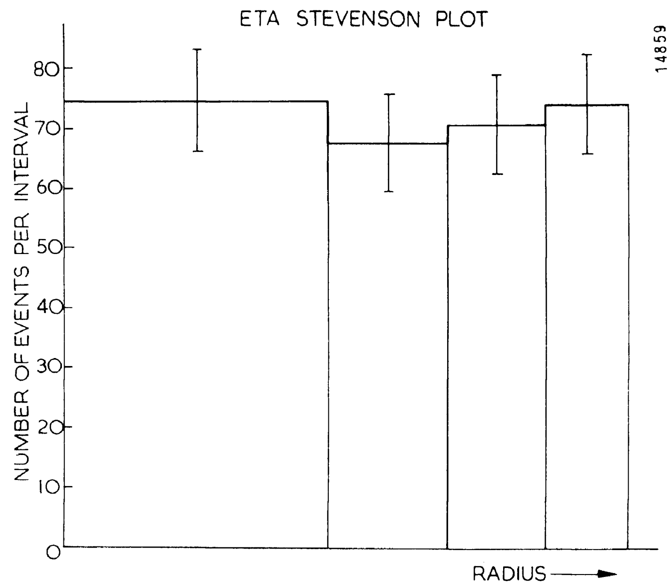


Fig. 10 Dalitz plot density (Stevenson plot) for η decay. (Collection of data.)

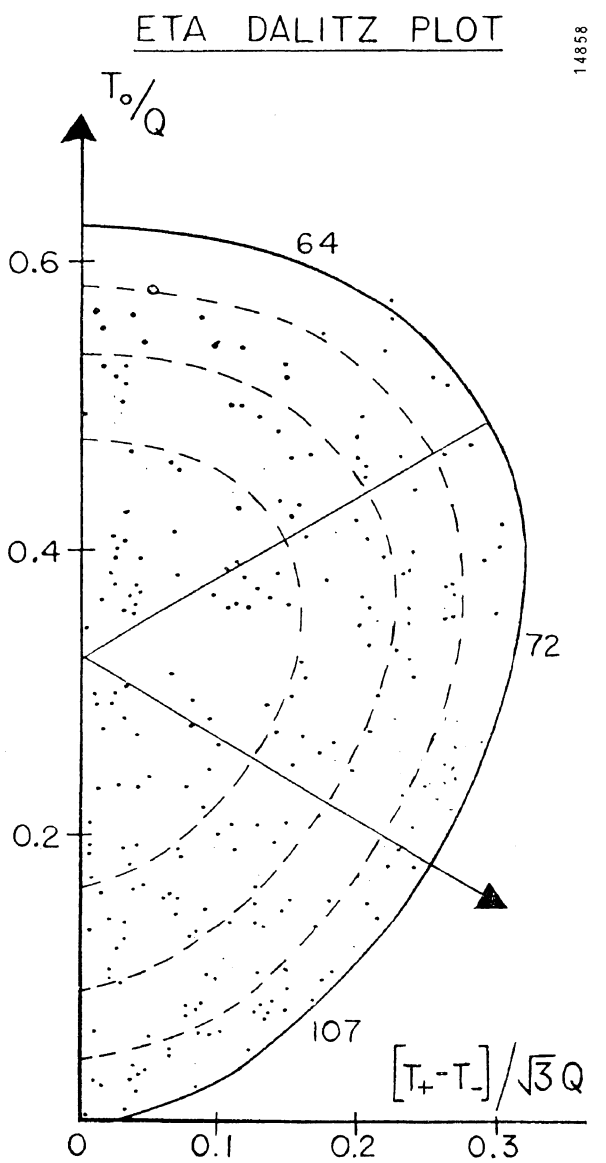


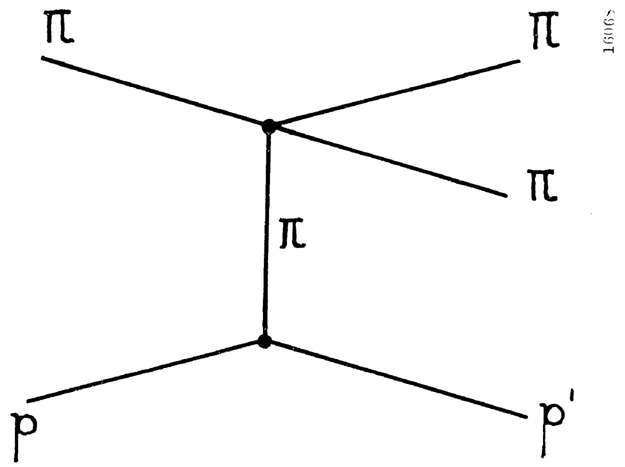
Fig. 9 Dalitz plot for η decay. (Collection of data.)

G = C = +1. Here the transition to $(\pi^+\pi^-\pi^0)$ must proceed through violation of G parity. Due to the fact that $\eta\rightarrow 3\pi$, the 0^+ state is excluded by parity and angular momentum conservation; of the three remaining 0^-, 1^+, 1^-, only 0^+ gives a uniform phase space population. The mechanism is then the following. The η particles are produced as 0^{-+} particles and through violation of G parity by e.m. interaction transform into 0^{--} final state. This is the well-known final state of the τ meson which is also almost uniform in its Dalitz plot. But in this transition where e.m. forces come into play, other channels are open and mainly, as said, the $\gamma+\gamma$ channel. On the other hand, there is another dominant mode that you expect, namely $\pi^+\pi^-\gamma$. Search for this channel has given negative results up to now.

On the other hand, an experiment on the photoproduction of η presented at this Conference, planned for detecting energetic γ rays coming from η decay into neutral modes, has given a positive result of the expected order of magnitude for the cross-section [10], although the experiment is not yet conclusive to discriminate the mode 2γ against $\pi^0+\gamma$. But the question of lack of $\pi^+\pi^-\gamma$ observation is not yet removed and for this reason some people prefer to wait some time before saying that the problem of quantum number assignment of the η is definitely solved.

ρ Chronologically this is the first structure discovered; after a long search by different experimenters [11], it was found by Erwin *et al.* at the right energy. This result was immediately confirmed by many authors [12] (Fig. 11). It deserves a long discussion because, in my opinion, it is the most difficult object to deal with. It reveals itself as a broad peak in the 2π mass distribution around 740 MeV with a width of the order of 100 MeV. Such a structure, if detected, in a future laboratory, in a free $\pi\pi$ collision would be called a resonance in $\pi\pi$ scattering in $I = 1$, $J = 1$ state.

Following the theoretical proposal made by Chew and Low [13], it is possible to measure the $\pi\pi$ cross-section by studying, in (πp) interactions, the peripheral collision between the incident pion and a virtual pion emitted by the nucleon. The process can be visualized with the simple graph



where the peripheral condition means that the 4-momentum transfer $\Delta^2 = (P' - P)^2$ to the nucleon must be small and small means " as small as possible " for the experimentalists. In reality small in the sense of Chew and Low means " as small as impossible " because the predictions of the theory are only strictly valid for $\Delta^2 = -\mu^2$, i.e. in the unphysical region of the process. The idea was, in order to measure the $\pi\pi$ cross-section, to determine for a certain mass M of the dipion system the cross-section in the physical region $\sigma_M(\Delta^2)$ as a function of the momentum transfer and to extrapolate this cross-section to $\Delta^2 \to -\mu^2$. Nobody has succeeded yet in doing a successful extrapolation, but a large peak in the mass spectra for the dipion system has been detected, outside the phase

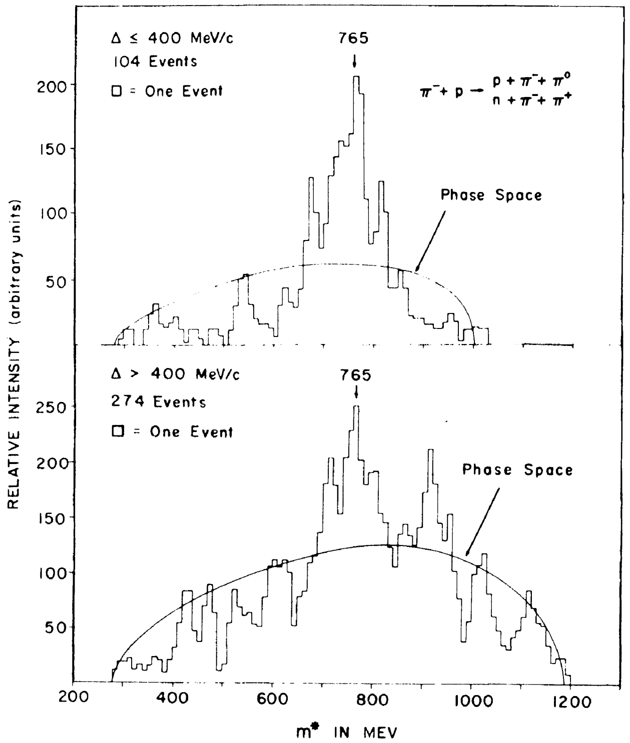


Fig. 11 Combined mass spectrum for the $\pi^-\pi^0$ and the $\pi^-\pi^+$ system, showing production of the ϱ for two ranges of 4-momentum transfers [11b].

space, in the aforementioned position for small momentum transfer. Excited by this finding, people have tried to use the Chew and Low formula, valid at $\Delta^2 = -\mu^2$, in the physical region with the hope that the process is still dominated in the near physical region by the first isolated singularity in the unphysical region. In this way something which we call a $\pi\pi$ cross-section has been calculated, which reflects essentially, beside kinematical factors, the peaking in the mass spectrum found experimentally.

What are the results concerning the region of the peak ?

(1) Its presence in all charge states ρ^+, ρ^-, ρ^0;

(2) A ratio of about 2 on the production of $\dfrac{\rho^0 + n}{\rho^- + p}$ in $(\pi^- + p)$ collision as expected from the peripheral model for a $I = 1$ dominant state;

(3) A well defined angular distribution for $\pi + \pi \to \pi + \pi$ scattering for the configuration $\pi^\pm + \pi^0$ with a dominant $\cos^2\theta$ term as expected for a $J = 1$ state (Fig. 12);

(4) An absolute cross-section at the peak $\sim 1/2$ to 2/3 of the one expected for a resonant p wave.

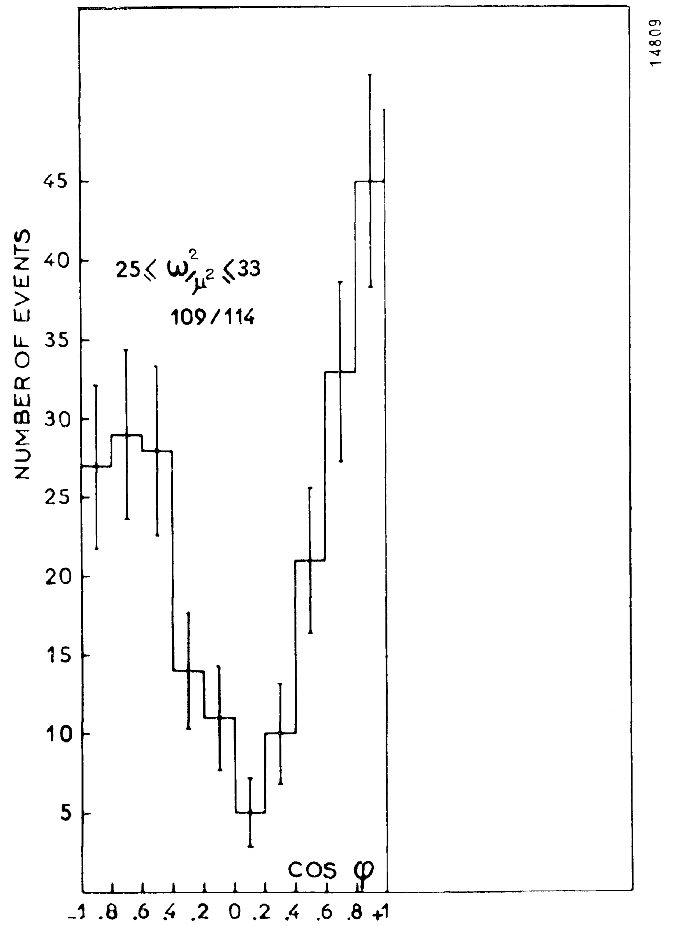


Fig. 12 Angular distribution for $\pi\pi$ scattering in the $\pi^{\pm}+\pi^0$ configuration in the mass range $25\mu^2$ to $33\mu^2$, showing a dominant $\cos^2\theta$ term.

This last finding which would speak against a resonance is mitigated by the observation, that the angular distribution over a wide range of $M_{\pi\pi}$ shows a clear interference effect, probably with an S wave, which changes sign just in the region of the peak. For that which concerns the validity of the peripheral model, a way to test it has been suggested by Yang and Treiman based on the fact that for an exchange of a π meson from the nucleon line to the four pion vertex, there must be no correlation between production and decay plane of the ρ. Experiment shows that this condition is verified only for very low momentum transfer (Figs 13, 14). Considering the results on the absolute cross-section as the weakest one, and taking into account the peripheral character of the production process, the information speaks clearly in favour of a well defined state of quantum numbers

$$(J, P, I, G) = (1, -1, 1, +1) = 1_1^{-+}$$

But despite the clarity of this conclusion about quantum number assignment, the behaviour of this object is quite complicated.

Everybody who has worked in this field in the GeV region knows that the profile of the ρ is very much like a mountain of jelly perturbed by an earthquake; the profile changes and sometimes protuberances appear in the mountain. The possibility has been put forward of a splitting into 2 separated peaks near 700 and 800 MeV in the ρ^0 configuration.

There has been a lot of discussion during the conference on this subject and I think I can present the following scheme. It is essential in what follows to distinguish between charged $\rho^{\pm}$ and neutral ρ^0.

Let us start with the charged one. Because it has a large width, its lifetime is very short and the distance travelled when produced with low velocity in the C.M. system is of the order of the radius of nuclear forces. This can have two consequences: interference

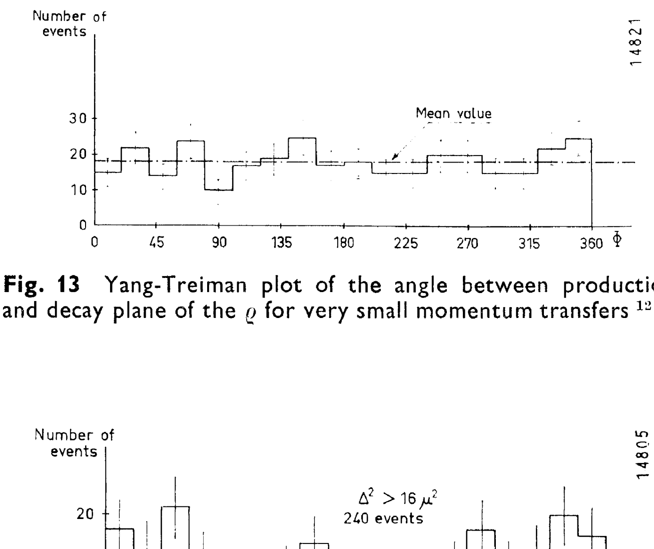


Fig. 13 Yang-Treiman plot of the angle between production and decay plane of the ϱ for very small momentum transfers [13c].

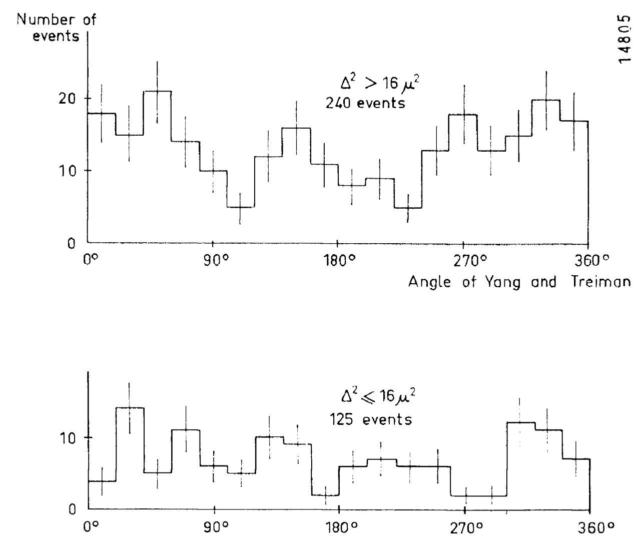


Fig. 14 Yang-Treiman plot for 4-momentum transfers $\Delta^2 > 16\mu^2$ and $\Delta^2 \leqslant 16\mu^2$, showing deviation from the peripheral model with increasing 4-momentum transfer.

with other processes like isobar formation, and broadening of its width. It is possible that the width we measure at low energy is greater than the actual width. Some results at higher energy tend to favour this interpretation. Also the position of the peak can change with energy and Δ^2; as a matter of fact some walking of the peak has been also reported.

It is necessary to point out here that there is no necessarily strict correlation between the shape of the resonance in the ideal free $\pi\pi$ collision and the actual shape of the peak in the peripheral collision of the incident π with an off mass-shell pion coming from the nucleon.

Returning now to ρ^0, the situation is complicated by the presence of the ω in the mass region of the ρ. Because the ω can decay at a non negligible rate, violating G parity, into 2π, there will be one more amplitude which interferes with the amplitude which gives the ρ^0, producing complicated patterns, in particular influencing the angular distribution in the region near the peak (Fig. 15).

We can expect both a dependence from the energy and from the momentum transfer for these phenomena: (1) from the energy because ω and ρ production can have different excitation functions, (2) from the momentum transfer because the ρ production is strongly dependent on the momentum transfer.

In my opinion a large amount of work is necessary before we can understand the pionic structures and in particular the physics of $\pi\pi$ collisions. I wonder whether some kind of agreement would not be possible among the main laboratories in order to save time and money in this field, as well as in other ones.

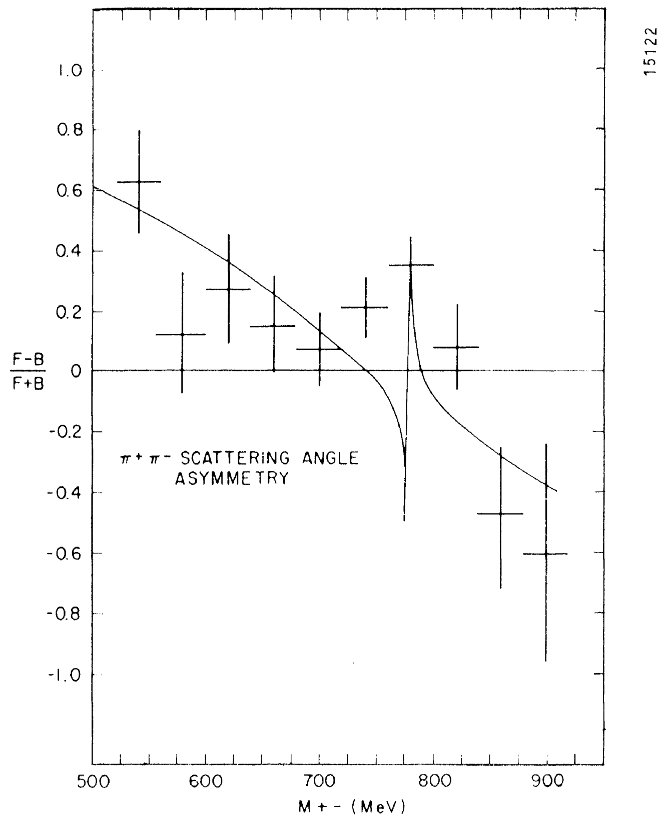


Fig. 15 Interference effect on the forward-backward ratio in $\pi^+\pi^-$ scattering [12b].

PRODUCTION OF ω, η, AND ρ

One of the major results to be extracted from the material presented at this conference is the proof that all three objects are produced in all strong interactions with sizeable cross-sections, when enough energy is available in C.M. system and, of course, when no selection rules forbid them.

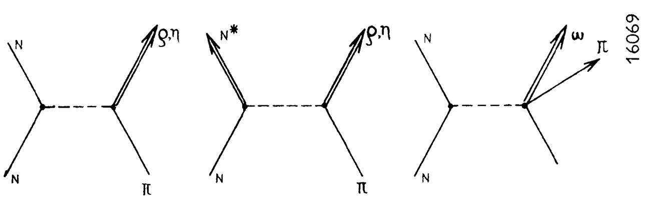
Among the others I will discuss in some detail two classes of production processes on nucleons, namely, those initiated by pions and by antiprotons.

In the πp collisions there can be, besides more complicated things at sufficiently high energy, essentially the following channels:

A	B	C	
$\pi+N\to N+\rho$	$\pi+N\to N^*+\rho$	$\pi+N\to N+(\pi+\rho)$	(1)
$\to N+\omega$	$\to N^*+\omega$	$\to N+(\pi+\omega)$	(2)
$\to N+\eta$	$\to N^*+\eta$	$\to N+(\pi+\eta)$	(3)

where N^* means the (3/2, 3/2) isobar of the nucleon.

Selection rules on G parity tell us that only processes $A(1)$ $A(3)$ $B(1)$ $B(3)$ and $C(2)$ can be due to one pion exchange contribution



which can manifest itself, in the appropriate energy region, as a marked peripherism. Let us remark that with the assignment of quantum number for the η given before, parity conservation forbids the peripheral production of the η. We know already that for the ρ meson this marked peripherism has been consistently observed many times in process $A(1)$. Some results at this conference show that peripherism is observed in reaction $B(1)$. The indication of its absence in process $B(2)$ confirms up to now, in a slightly indirect way, the G quantum number assignment. Unfortunately data on η production are still not adequate for such analysis, but will be available soon, I hope.

As an example of class A phenomena let us refer to the result at 1.23 GeV/c of π^+ on deuterium where $N+\omega$ and $N+\eta$ production amount to 1.2 mb and 0.9 mb respectively (3).

As an example of class B phenomena let us quote the results around 2.7 GeV in π^++p processes [14].

Here we have the following results:

$$\sigma(N^*_{++}+\rho) = 1.5 \text{ mb}$$

$$\sigma(N^*_{++}+\omega) = 1.3 \text{ mb}$$

$$\sigma(N^*_{++}+\eta) = 0.45 \text{ mb}$$

where in reactions initiated by π^- at $\sim$2 GeV the analogous reactions give cross-sections for $B+C$ of

0.45 mb 0.17 mb 0.09 mb respectively.

Here the enhancement due to the N^*_{++} isobar in the configuration $(p\pi^+)$ is evident. Examples of ω and ρ production in association with N^* are presented in Fig. 16.

It is of some interest to try to follow in the various energy regions the trend of the processes for multiple meson production. Below 1 GeV/c only 2π productions essentially occur and the process seems dominated by the nucleon isobar N^* formation. Above 1 GeV/c 2π production still dominates and the ρ meson seems to be the important feature.

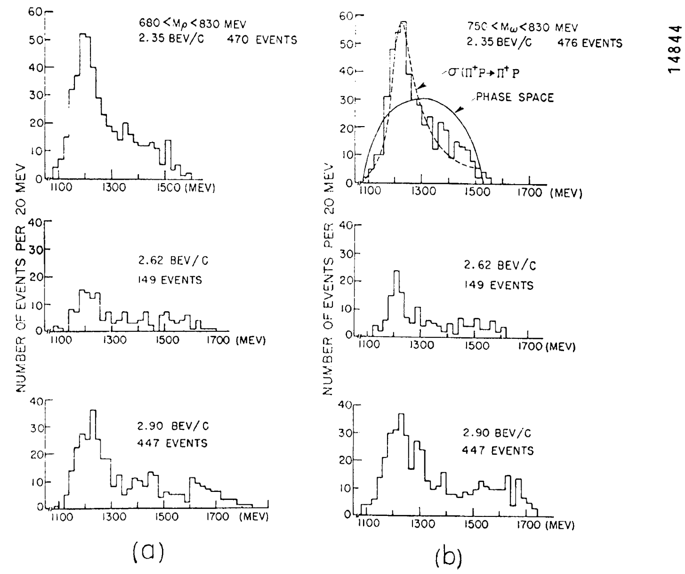


Fig. 16 Production of $N^*(3/2\text{-}3/2$ isobar) together with ρ and ω in π^++p interactions [14].

The 3π and 4π productions come into play with steep excitation functions; around 3 GeV it seems that the processes mentioned have nearly the same cross-section. Then other channels open and probably the mentioned ones individually decrease continuously. It is clear that from a detailed study of the behaviour of the various competing processes one can learn a lot on the mechanism of multipion production and relative coupling of various structures involved.

Turning now to antiproton-proton annihilation in the familiar 5π annihilation there has been a confirmation of ω production [2] and no clear evidence for the ρ; but ρ shows up instead quite clearly in 3π annihilation for antiproton at rest in each one of the 3 combinations $(\pi^+\pi^-)$ $(\pi^+\pi^0)$ $(\pi^-\pi^0)$ with equal strength (Fig. 17). The ρ is also seen in 4π annihilation of antiproton at 3.25 GeV/c in $I_z=0$ charge state. At this energy a search was made for 2ω production with a negative result.

Leaving now the sound ground of well established particles, let us talk briefly about a few more peculiarities in mass spectra drawn to the public attention before this conference.

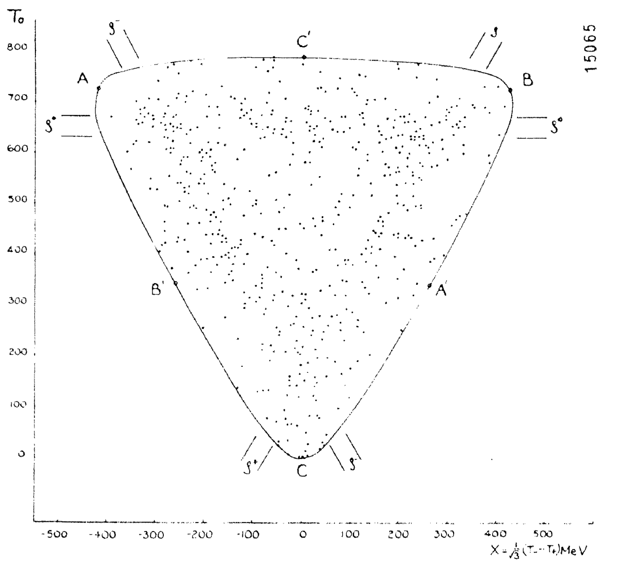


Fig. 17 Dalitz plot showing ϱ production in $\bar{p}p$ annihilation at rest [19].

ABC This is the name which people attach to the anomalous behaviour of the dipion mass spectrum around 300 MeV found in the experiment [15]

$$p+d=\begin{cases} H_e^3+X_0 & \text{(I)} \\ H^3+X^+ & \text{(II)} \end{cases} \qquad \text{where } X=2\pi$$

Subtraction of II/2 from I gives the contribution of 2π in $I=0$ state leaving us with a shape in violent disagreement with phase space just in the region from 280 up to 340 MeV. The absence of any effect in the H^3 spectrum has been confirmed [16]. The introduction of a $I=0$ $J=0$ scattering length of 2.8 $\hbar/\lambda c$ reproduces the anomaly but it seems so large that it sheds some doubt on this interpretation, and it leaves open the possibility of a new resonance in the physical region of the dipion.

Experiments on 2π production in $I_z=0$ are inconclusive up-to-now as proof or disproof of this fact, with the exception perhaps of two experiments presented at this conference. One is on photoproduction [10] of pion pairs $\pi^+\pi^-$ using spark chambers as detectors of the pairs, where a large peak around mass 310 MeV is evident, outside the simple phase space. The second one is an experiment of $\pi^+\pi^-$ production in π^-p collision at 310 MeV using a combination of multiscintillators and spark chambers [17] limiting the detection to very low momentum transfer ($\Delta^2<\mu^2$). There seems to be a clustering of points in the Dalitz plot around mass 300 MeV. On the other hand, there is some conflicting evidence from other studies.

In any case the ABC phenomenon is real and one has to find an explanation. One favoured hypothesis which avoids the introduction of a new resonance is that the phenomenon is produced by a pole of the $J=0$ $I=0$ dipion state in the near unphysical region, which influences the nearby physical region by its scattering length, strongly energy dependent.

ξ peak. This peak too came to the conference with a name already known. It was observed in the mass spectra of dipion and it was suggested to be another isovector like the ρ [18]. Its position was claimed around 580 MeV with small width <30 MeV. Conflicting evidence has been collected before and during this conference. In my opinion none of the experiments performed up to now have enough statistics to really prove or disprove it, thus it remains at present only a suggestion.

Peakology. This art, which proved so successful in the case of ρ, ω, η, has been pursued quite a lot with the result that many peaks are now claimed by different authors and unfortunately often in different positions, in the multipion spectra. The most frequent suggestions are around masses 400, 500, 600, 1000, 1200 MeV.

It has been absolutely impossible for me to reach any definite conclusion about this peaking affair, with the material presented at this conference. This conclusion does not mean that other peaks do not exist and perhaps more objects too. In particular the dipion is an object which justifies investigation in more detail. As a matter of fact I heard some rumour that in the theoretical domain there is an urgent need for finding a pathological D wave. The question of which one of these features is going to emerge from the darkness will be answered, I believe, quite soon.

Instruments. Although most of the physics I have presented here has been done with bubble chambers, the role of other instruments cannot be ignored. Spark chambers are enlarging their field of application and seem particularly adequate for precise measurements in definite configurations of important phenomena.

I have noticed the coming of other devices too, luminescent chambers and a bubble chamber of high Z material with a hydrogen target inside.

I heard a rumour of the successful test of a composite bubble chamber system consisting of a small H_2 bubble chamber inside a large propane one. I hope that the merits of all these new devices will be known shortly. In the future this kind of physics will be much more complicated and perhaps, to some extent, less rewarding and then the disposal of different instruments will give a unique chance to choose not only the best experiment to do with a certain technique, but also the counterpart, the best technique to solve a definite problem.

In conclusion, despite a certain confusion which remains in my mind, I feel happy about the physics which we have now and which we can foresee in the near future. It seems to me that with the study of those pionic structures and especially with the study of the $\pi\pi$ interaction we are playing a game of some fundamental character, like the one we played with nucleon-nucleon, pion-nucleon interaction, and, may be, even better.

ACKNOWLEDGMENTS

The following figures in this report are reproduced by kind permission of the Editor of Physical Review Letters:

Figures 2, 3b, 7, 8 and 11.

We wish to thank the Editor and the authors of the papers concerned.

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DISCUSSION

McMillan: I will make one comment myself on a remark made by Puppi towards the beginning of his talk in which he showed some prejudice for preferring to call those things particles which have small widths. I would like to point out that the deuteron has a smaller width than the neutron and therefore, following this principle, would be a more fundamental particle.

Yamaguchi: Is $\eta \to 2\gamma$ confirmed experimentally?

Salvini: As we reported before, we observe a radiative decay which could be either the decay $\eta \to \pi^0 + \gamma$ or $\eta \to \gamma + \gamma$. As yet we cannot decide between the two modes. Therefore we cannot contribute on the question of the η spin (0 or 1) at this time. However our results do seem to exclude the $\eta\zeta$ degeneracy if ζ exists(*).

ALVAREZ: In view of the interest in the neutral decay mode of the η and since at first sight it appears to be almost impossible to decide the question experimentally, the conference members may be interested in the experimental situation as it is developing. Several groups using the 72″ bubble chamber films have already measured a total of about 40 converted γ rays which arise from the neutral decay of η mesons. We estimate that altogether there are about 200 of these in the film. One can transform the observed γ to the η C.M. system, and so determine the emitted γ ray spectrum. In the next few months it should be possible to make definite statements about the partial rates into $\gamma+\gamma$, $\pi^0+\gamma$ and into states of higher final γ ray multiplicity.

BLOCK: The data we presented from neutral decay mode of the η from the $\pi+d\to p+p+$neutrals experiment of Pevsner *et al.*, indicate that the spectrum of γ-rays is compatible with a 50-50% mixture of $\eta\to 2\gamma$ and $\eta\to 3\pi^0$, and *not* with 2 γ being predominant. It must be stressed that these conclusions are made with the assumption of 0^{-+}. If we do not assume this, we are not able to distinguish these events from $\pi^0+\gamma$ (+background of $2\pi^0$), the prediction for 1^{--}.

BERNARDINI: I would like to know if these interference effects you mentioned in your talk concerning the interference between the $J=0$ and the $J=1$ state, are very clear. Does this mean that an S-state pion-pion interaction is also definitely established? If this is so, what is the energy dependence of the S-state interaction?

PUPPI: I think the presence of the interference effect is very well established by two different experiments, one dealing with the ϱ^+ and the other dealing with the ϱ^-. It looks as if there is a destructive interference between the ϱ and another partial wave which is repulsive. Because the interference effect goes quite smoothly at the low energy side, if we plot the fore/aft asymmetry against the energy, the simplest interpretation is in terms of an s-wave. In this case, the two states which interfere are a $T=1$, $J=1$ (p-wave) and a $T=2$, $J=0$ (s-wave). If you look to the neutral ϱ configuration (see Fig. 15), then the interference seems to go in the opposite way with energy. There is also some strange behaviour around the ϱ mass value. Those interference patterns go through zero just at the ϱ mass. For this reason I think this typical kind of pattern where the interference changes sign, is a strong support that the phase of the other wave passes through 90° unless the two s-waves are both pathological just at this point.

BERNARDINI: The ABC was supposed to be in an s-state. What are your feelings? Is this s-wave a continuation of the ABC, or is the ABC so narrow that it cannot have anything to do with it.

PUPPI: None of the experiments which show this feature are able to accumulate enough statistics in the very low mass region, and therefore I think the question of finding the ABC inside the ϱ structure is an open one.

SELOVE: I would like to make a comment about the angular distribution of $\pi^-\pi^+$ scattering, at the ϱ mass. Data from a number of experiments agree in showing a very strong forward peaking for $\pi^-\pi^+$, while $\pi^-\pi^0$ is closely symmetrical forward-backward. The data from our own experiment, which join smoothly to data from others, show a complete asymmetry, with no backward scatterings at all.

I have tried to fit our data by a mixture of s, p, and d waves. The best fit I can make, within the statistics of the experiment, cannot give quite such complete cancellation of backward scattering; the odds against fitting the data are about 100 to 1. Of course the calculation was with neglect of final-state (π-nucleon) interactions, and also assumed the s, p, and d scattering to be purely elastic.

It may be useful to use a different model for thinking about these $\pi-\pi$ scattering data, and that is a model viewing the $\pi-\pi$ scattering as an exchange scattering rather than merely as some combination of different partial waves. The experimental data are reminiscent of $n-p$ scattering, with contributions of charge-exchange and non-charge exchange type. In this view the $\pi^- - \pi^+$ would show no charge-exchange (i.e., backward) scattering because the exchanged object—presumably a ϱ—carries a maximum charge of only one unit.

PUPPI: In the mass region of the ϱ^0 many laboratories consistently found very strange behaviour of the angular distribution. In particular, they have a tremendous forward-backward ratio. This is essentially like an anomaly because the interference changes sign, and one of the explanations which has been proposed for this anomaly, just near the peak of the object, is an interference with the two pions which come from the ω, violating G parity.

MAGLIC: The Dalitz plot of the η shows an anomaly, namely the π^0 kinetic energy is lower than that of π^+ or π^-. Is this asymmetry observed in all experiments? This would be interesting to know in order to understand if there is some final state $\pi^+\pi^-$ interaction in the decay of η. About the decay modes of ω, a good slide was shown at the conference with an indicative evidence for the ω—$\pi^+\pi^-\gamma$ by a Dubna group. This is the first time that this mode is seen.

SALAM: What are the relative production ratios of ϱ ω and η in the reactions:

$$\begin{array}{llll} \pi+N \to & N+\varrho & \text{and } p+\bar{p} \to & \pi+\varrho \\ & N+\omega & & \pi+\omega \\ & N+\eta & & \pi+\eta \end{array}$$

PUPPI: I can give you some information at 2.7 GeV, concerning the $\pi+p$ reactions. The cross-sections are 1.5 mb, 1.3 mb, 0.45 mb, they are comparable. In the $p\bar{p}$ I do not have the numbers.

HEISENBERG: May I just make one remark concerning which particles are more important than others. From the lecture of Puppi it seems that among the boson-family the four particles π, ϱ, η, ω are the most important. I want to draw attention to the fact that using the old idea of Fermi and Yang, just these four states (and only these) can be considered as composed of a nucleon and an anti-nucleon in an S-state. Even if one favours the general picture that in the words of Chew, all particles are composed of all particles, the Fermi-Yang picture

(*) After this conference, strong evidence for spin zero of the η was presented by Chrétien *et al.*, (Phys. Rev. Letters, to be published) as a result of the observation $\eta\to\gamma+\gamma$.

will be a good approximation, which seems to be confirmed by the experimental situation.

SEGRÈ: We have heard a few days ago that in $p\bar{p}$ annihilation at rest, polypions are frequently produced. In annihilation in flight, at about 1 GeV energy, the polypions seem to disappear. What is the explanation of this phenomenon?

WEISSKOPF: Why does the η particle not appear in $\bar{p}-p$ annihilation?

PUPPI: It is my own impression and I think that of many people working in this field, that when you enlarge the phase space it becomes more and more difficult to see a resonance in the large background of other processes.

ARMENTEROS: I just want to say that we have some evidence for the η, but in our choice of events which consists essentially of annihilation with a K_1^0, we are very badly let down by phase space.

ROSENFELD: I just want to comment on Weisskopf's question again; I said this before, but I don't think this is so surprising that the η is hard to see in antiproton annihilation, because *first* ,compared with the ω there is about a factor 3 in statistics for the spin. *Second,* only ¼ of the η decay into $\pi^+\pi^-\pi^0$ which is easy to see, this makes a factor of 12 against detection of the η and I think that with this factor the experiments are just not good enough, yet. I don't think, in other words, that η production in antiproton annihilation is at all surprisingly small.

NUCLEON-NUCLEON SCATTERING (*)

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The present report deals with the classical problem of high-energy physics, the problem of nucleon-nucleon interactions. In this general investigation we confined ourselves to energies below 1 GeV. In this energy zone the main data and their analysis relate to energies below the threshold of pion production. A big programme of experimental investigations has been implemented in the last few years in the 500-700 MeV range, mostly at Dubna but also at Bristol and Chicago. As previously, interest was centred mostly on the energy region below the threshold of pion production. The relatively high intensity proton beams available made it possible to carry out high precision experimental research, although it takes time to perform the complicated experiments for the study of triple scattering.

Among the papers given at the present conference, it is possible to draw a distinction between three different groups of work. To the first group belong the experimental investigations in the " elastic region ", below the threshold of pion production in nucleon-nucleon collisions. To the second group belongs the collection of data on nucleon interactions in the 500-700 MeV region which is very difficult to analyse. To the third group belong the results of the systematic phenomenological phase analysis of data on the elastic interaction of protons with protons and neutrons. The joint analysis of data concerning both the *pp* and the *np* systems is very fruitful [1]. As a result of the well-known contribution by Puzikov, Ryndin and Smorodinskij [2], it became clear that, to find a single set of phase shifts from experimental data on the elastic scattering of particles when the spin effects are not negligible, it is usually necessary to perform a considerable number of independent experiments. In the elastic region below the threshold of pion production, the number of such experiments is equal to the number of scalar amplitudes in the general transition amplitude. The problem of nucleon-nucleon scattering was discussed in 1959, from this point of view, by Smorodinskij at the Kiev conference.

(*) The CERN Organising Committee wishes to take this opportunity of thanking Dr. Lapidus for undertaking, at short notice, the task of preparing a written report on the papers submitted on this subject for the parallel session.