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REPORT ON NON BARYONIC RESONANCES

by

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REPORT ON NON BARYONIC RESONANCES *

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INTRODUCTION

This report is divided into three sections: the first deals with production modes and phenomenological characteristics of the pion resonances; in the second some theoretical considerations are made on the pion resonances; the third part deals with strange isobars.

We do not claim that our list of references is by all means exaustive and/or complete. In fact, as things go nowadays we are afraid that it is not even up to date.

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Resonances Characterized by Pion Decay-Experimental Results

W. Vernon

This report is essentially a listing of production modes and some of their characteristics for the ρ, ω and η resonances. Also included are a list of new and uncertain "bumps" and some meager information of the f^0 and ABC resonances. The main source of information has been the 1962 CERN conference report, but a search through Physics Review Letters and Nuovo Cimento has also been made. Recommended reading on the present stage of resonances is Puppi[21] for a general summary; Saclay report (to appear in N. Cim.) on the ρ; Stenvenson et al[40] for quantum numbers of the ω; Steinberger et al[5] for the best statistics on the η decay.

Various interesting effects are also listed in the comments column of the table and are not necessarily available for all production modes and authors (see the "Explanation of production table"). The pion-pion scattering cross-section which is perhaps derivable from the ρ production is not kept track of; however an example is given in fig. 11. No authors seem to have obtained sufficient statistics to allow an extrapolation to the non-physical region of momentum-transfer required by the original Chew-Low formula. The Selleri formula[50] for real Δ (4-momentum transfer to the nucleon) is currently fashionable. It seems definitely assured that the ρ is created in low momentum-transfer interactions ($\Delta^2 < 30\ \mu^2$) with the exception of one case[18]. The Treiman-Yang test[51] is found to be favorable for one-pion-exchange for Δ in the ρ creation range by the Saclay group[23], but unfavorable by Pickup et al[28]. Since pion-pion extrapolated cross-sections assume the validity of the OPE model, it seems best to wait a while before accepting $\sigma_{\pi\pi}$ constructed by ρ generating processes.

Curious aspects of the ω and η now seem to center on their several decay modes. Various branching ratios are indicated when they are known, but some comment should be made about the possibility of ρ-ω interference in the case of the forbidden 2π decay of the ω. This has been pointed out by Feinberg[76] and looked for by Walker[3] and Pickup[28]. Such searches are refered to as "splitology". Although the mass difference is not small (as it is in the case of the K_1^o and K_2^o), the wide ρ still allows some interference, the effect of which is to enhance the 2π decay of the ω compared to what it would be in the absence of the ρ. In lower resolutions experiments such effects might shift the apparent centroid of the ρ peak, or the ρ might be moving anyway, independent of the resolution and coupled in some strange way to the two pion ω decay. Notice the ranges of mass values for the ρ as a function of energy (fig. 12) and mode of production. The list also shows that the ω peak is still moving around, which leaves the η as the only stationary mass point.

Explanation of the Table

a) σ is the cross-section for production and decay into the mode shown.

b) Γ is the full width at half-maximum of the peak.

c) η (in the comments for the ρ) means the number of outgoing π emitted forwards minus the number emitted backwards divided by the total number (for ρ^o the outgoing pion is usually the π^-).

The reference direction is with respect to the incident π in the rest frame of the ρ.

d) The Treiman-Yang test of the One-Pion-Exchange model is listed only for the ρ where the angle α is defined as the angle between the plane of the incident and outgoing pions (pion production of the ρ). Basically the test says the angular distributions of the decay pions should be independent of α.

RESONANCE TABLE (ρ, ω, η)

Charge	Reference	Mode of production	Incident momentum in $\frac{\text{BeV}}{c}$	Mass	Γ	σ Production in mb	Comments
ρ^+	2 44	$\pi^+ + p \rightarrow (\pi^+ + \pi^0) + p$	1.03 1.22 1.4	713±81 726±10 755±24	31±143 57±27 61±24	.19 ± .07 .39 ± .09 .57 ± .08	$\frac{\rho^+ \rightarrow 2\pi^+ + \pi^- + \pi^0}{\rho^+ \rightarrow \pi^+ + \pi^0} < 2 \pm 1\%.$ $\frac{\rho^+ \rightarrow \pi^+ + \text{others neutrals}}{\rho^+ \rightarrow \pi^+ + \pi^0} < 10 \pm 10\%$
ρ^+	5 27	$\pi^+ + p \rightarrow (\pi^+ + \pi^0) + p$	2.34 2.62 2.9	770±10	130±10	2.1 ± .3 1.4 ± .2	Production angular distribution for $N^{*++} + \rho^0$ is presented.
ρ^0	5 27	$\pi^+ + p \rightarrow \pi^+ + p + (\pi^- + \pi^+)$	2.34 2.6 2.9	750±10	100±10	1.4 ± .25 1.4 ± .25 .95 ± .2	
ρ^0	14	$\pi^+ + d \rightarrow p + p + (\pi^+ + \pi^-)$	1.23	~750	-	-	quite high background.
ρ^0	28 29	$\pi^- + p \rightarrow$ $\pi^- + \pi^+ + \gamma$ (1) $(\pi^- + \pi^0) + p$ (2)	1.4	740	100	-	Do Treiman-Yang test $\frac{\sigma(2)}{\sigma(1)} = 0.585 \pm 0.31$ Decay angular distribution as function of Δ is given.
ρ^-	3 43	$\pi^- + p \rightarrow (\pi^- + \pi^0) + p$	1.89 2.1	740	120	-	Split in the peak at about 775 MeV.
ρ^-	7	$\pi^- + p \rightarrow (\pi^- + \pi^0) + p$	2.8 7.2	780	100	-	

Charge	Reference	Mode of production	Incident momentum in $\frac{\text{BeV}}{c}$	Mass	Γ	σ Production in mb	Comments
ρ^{-} ρ^{0}	23 30	$\pi^{-}+p \rightarrow (\pi^{-}+\pi^{0})+p$ $(\pi^{-}+\pi^{+})+n$	1.6	740	100	.8 ± .2 1.1 ± 1	Treiman-Yang test is applied. **Are given:** η as function of Δ, mass plots as functions of Δ, decay angular distribution as function of $\Delta (\eta \sim .5)$.
ρ^{0}	19 31	$\pi^{-}+p \rightarrow (\pi^{-}+\pi^{+})+n$	6.0	750	100	.5 ± .2	Mass plots as a function of Δ.
ρ^{0}	20	$\pi^{-}+p \rightarrow (\pi^{+}+\pi^{-})+n$	12.0 17.0	725	50	.025	
ρ^{0}	4	$\pi^{-}+p \rightarrow (\pi^{-}+p)+$ $+(\pi^{-}+\pi^{+})$	2.03	–	–	–	High background.
ρ^{0}	6	$\pi^{-}+p \rightarrow \pi^{-}+p+$ $+(\pi^{-}+\pi^{+})$	4.7	–	–	–	
ρ^{0}	18	$\pi^{-}+p \rightarrow (\pi^{+}+\pi^{-})+$ neutrals	10.0	?			Dominant production seems to be from high $(>40\ m^{2})\ \Delta^{2}$
ρ^{0}	9	$\pi^{-}+p \longrightarrow$ $p+\pi^{+}+\pi^{-}+\pi^{-}$	7.0	750	100	–	$\eta = .53$

Charge	Reference	Mode of production	Incident momentum in $\frac{BeV}{c}$	Mass	Γ	σ production in mb	Comments
ρ^0	8	$\pi^- + p \Rightarrow N + (k\pi)$	7.2	–	–	–	Something here, but what ?
ρ^- ρ^0	32	$\pi^- + p \Rightarrow$ $(\pi^- + \pi^0) + p$ $(\pi^- + \pi^+) + n$	3.0	750 750	–	–	
$\rho^{\pm 0}$	10 33	$\bar{p} + p \Rightarrow \pi^+ + \pi^- + \pi^0$	stop $\bar{p}$	760	100	—	2.7 ± 6% of annilations to $\rho + \pi$. Data indicates decay from ^3S, protonium state.
ρ^0 $\rho^\pm$	11	$\bar{p} + p \Rightarrow$ $2\pi^+ + 2\pi^-$ (1) $2\pi^+ + 2\pi^- + \pi^0$ (2)	stop $\bar{p}$	720 750	100 100	–	← very high background for ρ^0. $\frac{\rho^0 \Rightarrow 2\pi^- + 2\pi^+}{\rho^0 \Rightarrow \pi^- + \pi^+} < 2.5\%$
ρ^0 $\rho^\pm$	12	$\bar{p} + p \longrightarrow 4\pi$ 5π	3.25	750 700	150 100	$3.9 \pm .1 (\rho^0)$ $.5 \pm .2 (\rho^0)$ $.18 \pm .2 (\rho^\pm)$	
ρ^+	41	$p + p \longrightarrow d + (\pi^+ + \pi^0)$	2.05	730			
ρ^0	45	$\gamma + p \rightarrow (\pi^+ + \pi^-) + p$		720			
							$\longrightarrow \omega \ (1_0^{--})$
ω^0	5 27 34	$\pi^+ + p \rightarrow$ $\pi^+ + p + (\pi^+ + \pi^- + \pi^0)$	2.35 2.6 2.9	782±1	20 (inst)	$1.8 \pm .2$ $1.8 \pm .2$ $1.6 \pm .2$	Production angular distribution. Polarization distribution → angle between decay plane and production plane.

Charge	Reference	Mode of production	Incident momentum in $\frac{BeV}{c}$	Mass	Γ	σ production in mb	Comments
ω^o	4	$\pi^- + p \rightarrow$ $\pi^- + p + (\pi^- + \pi^+ + \pi^o)$	2.03	785	80	.142 ± 0.31	Claims enhancement of ω^o production due to associated $N^*_{3/2\ 3/2}$. Plot of ω^o against Δ^2 shows ω^2 production independent of Δ^2.
ω^o	42 15	$\pi^+ + d \longrightarrow p + p$ $\begin{cases} + (\pi^+ + \pi^- + \pi^o) \\ \text{or neutrals} \end{cases}$	1.23	769	24 (inst.)	1.3 ± .4 charged mode	no real peak for neutrals $\Longrightarrow$ $\frac{\omega \rightarrow \text{neutrals}}{\omega \rightarrow \text{charged}} < 7 \pm 6\%$ Given production angular distribution
ω^o	23	$\pi^- + p \longrightarrow$ $\pi^- + p + (\pi^+ + \pi^- + \pi^o)$	1.59	780	20 (inst.)	0.23 ± 0.05	find = $\frac{\omega^o \rightarrow \pi^+ + \pi^-}{\omega^o \rightarrow \pi^+ + \pi^- + \pi^o} \sim 7\%$
ω^o	3	$\pi^- + p \longrightarrow$ $\pi^+ + \pi^- + ?$ $n + \pi^- + \pi^+$	1.89 2.1	–	–	–	$\frac{\omega \rightarrow 2\pi}{\omega \rightarrow 3\pi} \sim 15\%$ – 2π mass value at 780.
ω^o	11	$\bar{p} + p \longrightarrow$ $2\pi^+ + 2\pi^- + \pi^o$	stop $\bar{p}$	783	16	–	
ω^o	13	$\bar{p} + p \longrightarrow$ $K^+ + K^- + (\pi^+ + \pi^- + \pi^o)$ $K^+ + K^-$ + neutrals	stop $\bar{p}$	790 ± 1.6 790 ± 3.4	13 14.5		$\frac{\omega^o \rightarrow \text{neutral}}{\omega^o \rightarrow \text{charged}} \sim 21 \pm 7.5\%$
ω^o	46	$\bar{p} + p \longrightarrow$ $3\pi^+ + 3\pi^- + \pi^o$	1.61	780	18	.6 ± .15	

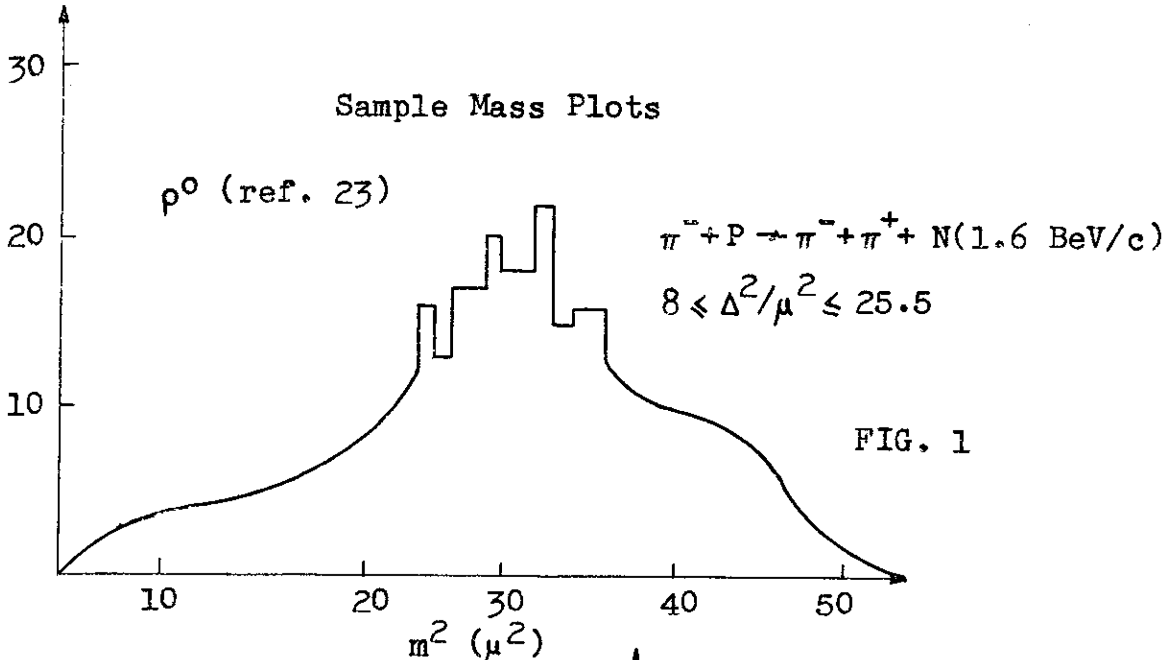
Charge	Reference	Mode of production	Incident momentum in $\frac{\text{BeV}}{c}$	M	Γ	σ production in mb	Comments
ω^0	35 36	$p+p \rightarrow$ $p+p+(\pi^-+\pi^++\pi^0)$	3.7	766 ± 4	25	$.048 \pm 0.013$	
							$\longrightarrow \eta(0_0^{-+})$
η^0	2 49	$\pi^+ + p \rightarrow$ $\pi^+ + p + (\pi^+ + \pi^- + \pi^0)$	1.22 1.4	548 ± 1 551 ± 2	-	$.075 \pm 0.015$ $.1 \pm .03$	$\frac{\eta^0 \rightarrow \pi^+ + \pi^- + \gamma}{\eta^0 \rightarrow \pi^+ + \pi^- + \pi^0} < .25$
η^0	5 27 34	$\pi^+ + p \rightarrow$ $\pi^+ + p + (\pi^+ + \pi^- + \pi^0)$	2.35 2.6 2.9	548 ± 1	-	$.75 \pm .15$ $.75 \pm .18$ $.80 \pm .15$	Good statistics yielding a good decay Dalitz plot $\frac{\eta \rightarrow \text{neutral}}{\eta \rightarrow \text{charged}} = 2.5 \pm .5$
η^0	25	$\pi^+ + p \rightarrow$ $\pi^+ + p + \left(\pi^- + \pi^+ + \begin{Bmatrix}\pi^0 \\ \gamma\end{Bmatrix}\right.$	1.17	547.5 ± 1	-	-	$\frac{\eta \rightarrow \pi^+ + \pi^- + \gamma}{\eta \rightarrow \pi^+ + \pi^- + \pi^0} = .26 \pm .08$ This removes the stumbling block for the 0 assignment.
η^0	17	$\pi^+ + p \rightarrow$ $\pi^+ + p + (\pi^- + \pi^+ + \pi^0)$ $\pi^- + p \rightarrow$ $\pi^- + p + (\pi^- + \pi^+ + \pi^0)$	1.27	548	-	.1 .0047	They have employed the trick of using the π^+ which gives m closest to the η^0 (in m of $(\pi^+\pi^-\pi^0)$ - Removes background. The ratio of these 2 productions should be 9:1 if $\eta^0 + N^*$ is the dominant production.
η^0	4	$\pi^- + p \rightarrow$ $(\pi^+ + \pi^- + \pi^0) + \pi^- + p$	2.03	550	-	$0.031 \pm .01$	
η^0	26	$\pi^- + p \rightarrow$ $n + \eta^0 \rightarrow \text{neutrals}$	1.096	545 ± 30	-	-	$\frac{\eta \rightarrow 3\pi^0}{\eta \rightarrow 2\gamma} = 1.1 \pm .3$ They look at distribution of opening angles in γ conversion

Charge	Reference	Mode of production	Incident momentum in $\frac{BeV}{c}$	M	Γ	σ production in mb	Comments
η^o	1	$\gamma+p \longrightarrow$ $\left\{\begin{matrix}\pi^o+\gamma\\ \gamma+\gamma\end{matrix}\right\}+p$ $\begin{matrix}1\\2\end{matrix}$	.94–1.0 1.01–1.2	1) 550 2) 520			$\left.\begin{matrix}1) \longrightarrow 5 & 2) \longrightarrow 2.5\\ 1) \longrightarrow 3 & 2) \longrightarrow 1.5\end{matrix}\right\} 10^{-32} cm^2/st$ proton is detected at:
η^o	24	$\gamma+p \to p+\eta^o$	excitation curve			Production limits	upper $\left.\begin{matrix}-0.38 \pm .72\\ +0.43 \pm .3\\ +0.23 \pm .19\end{matrix}\right\} \frac{ub}{st.rd.} \left\{\begin{matrix}440\\550\\638\end{matrix}\right\} \frac{MeV}{c}$ proton outgoing (35– 25°)
η^o	15 42	$\pi^+ + d \to p+p$ $(+\pi^+ + \pi^- + \pi^o)$	1.23	546	14	.22 ± .06	Given production angular distribution.
η^o	16	$\pi^+ + d \to p+p$ + neutrals	1.23	550		.68 ± .2	$\Big\} \Rightarrow \frac{\eta^o \longrightarrow \pi^+ + \pi^- + \pi^o}{\eta^o \longrightarrow \text{neutrals}} = 0.32 \pm\ 0.1$
η^o	48	$p+p \longrightarrow$ $p+p+\pi^+ + \pi^- + \pi^o$	2.	546±4		0.057±0.010	$\sigma(\eta \to \text{neutrals}) = 0.14 \pm 0.055$ $\frac{\eta \to \text{neutrals}}{\eta \to \pi^+ + \pi^- + \pi^o} = 2.5 \pm 1$ $\sigma(\eta \to \pi^+ + \pi^- + \gamma) < 5\,\mu b$ $\frac{\eta \to \pi^+ + \pi^- + \gamma}{\eta \to \pi^+ + \pi^- + \pi^o} < 9\%$
η^o	47	$K^- + p \to$ $\Lambda + \eta^o \to$ charged	0.76 0.85			0.15±0.05 <0.02±0.02	$\Bigg\} \Longrightarrow \frac{\eta^o - \pi^+ + \pi^o + \pi^-}{\eta^o \to \text{neutrals}} = 0.31 \pm 0.11$ at 700 $\frac{MeV}{c}$
		$K^- + p \to$ $\Lambda + \eta^o \to$ neutrals	0.76 0.85			0.48±0.10 <0.02±0.02	

Table of New and/or Lesser Resonances and "Bumps"

Mass (MeV)	Combination	Production	Number in peak	Width	Reference
990 - 1000	$\pi^{-}\pi^{0}$	$\pi^{-}+p \rightarrow (\pi^{-}+\pi^{0}) + p$	50	150 MeV	7
	$\pi^{-}\pi^{-}$	$\pi^{-}+n \rightarrow (\pi^{-}+\pi^{-}) + p$	20	150 MeV	
	$\pi^{-}\pi^{-}$	$\pi^{-}+p \rightarrow 2\pi^{-}+2\pi^{+}+n+(n\pi^{0})$	10	100 MeV	8
	$\pi^{+}\pi^{+}$	"	16	100 MeV	
585 - 600	$\pi^{+}\pi^{+}$	"	10	150 MeV	
	$\pi^{-}\pi^{-}$	"	16	150 MeV	
	$\pi^{-}\pi^{-}$	$\pi^{-}+n \rightarrow \pi^{-}+\pi^{-}+p$	10	100 MeV	7
	$\pi^{-}\pi^{-}$	$\pi^{-}+p \rightarrow \pi^{+}+p+(\pi^{-}+\pi^{-})$	15	85	13
	$\pi^{-}\pi^{-}$	$\pi^{-}+d \rightarrow p+p+\pi^{-}+\pi^{-}$	20		14
560	$\pi^{+}\pi^{0}$	$p+p \rightarrow d+\pi^{+}+\pi^{0}$	7	~30 MeV	41
580	$\pi^{+}\pi^{0}$	$\pi^{+}+p \rightarrow \pi^{+}+\pi^{0}+p$	35 tot	~50 MeV	22
	$\pi^{-}\pi^{0}$	$\pi^{-}+p \rightarrow \pi^{-}+\pi^{0}+p$	5	40	23
	$\pi^{-}\pi^{+}$	$\pi^{-}+p \rightarrow \pi^{-}+\pi^{+}+N$	5	40	
520	$\pi^{-}\pi^{+}$	$\pi^{-}+p \rightarrow k\pi+N$	80	70	6
395	$\pi^{-}\pi^{+}$	$\pi^{-}+p \rightarrow k\pi+N$	120	50	
325 - 350	$\pi^{-}\pi^{-}$	$\pi^{-}+p \rightarrow 2\pi^{-}+\pi^{+}+n\pi^{0}+p$	14	50	9
	$\pi^{-}\pi^{-}$	$\pi^{-}+p \rightarrow 3\pi^{-}+3\pi^{+}+n+k\pi^{0}$	20	50	8
	$\pi^{-}\pi^{-}$	$\pi^{-}+p \rightarrow 2\pi^{-}+2\pi^{+}+n+k\pi^{0}$	15	50	8
1250	f^{0}	$\pi^{-}+p \rightarrow (\pi^{-}+\pi^{+}) + n$		100	32
1260 ± 30		$\pi^{-}+p \rightarrow (\pi^{+}+\pi^{-}) + n$		~100	19 31
305	A B C	$p+d \rightarrow He^{3} + \pi^{+}+\pi^{-}$ $\pi^{0}+\pi^{0}$		~30	37 38 39

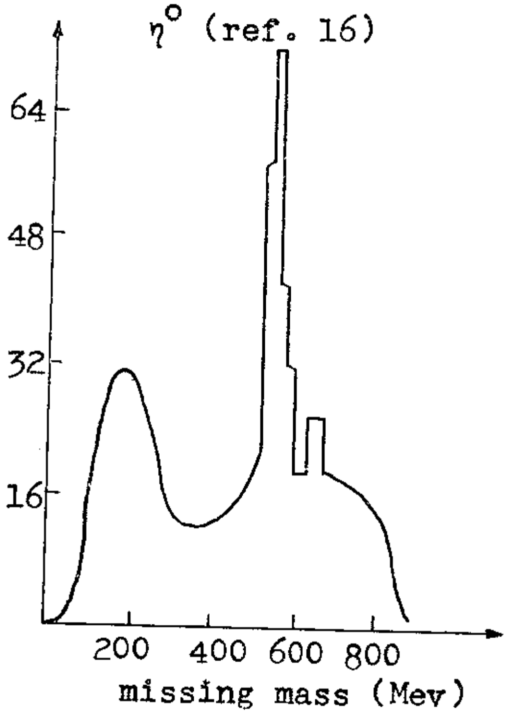
Sample Mass Plots



$\pi^- + P \rightarrow \pi^- + \pi^+ + N$ (1.6 BeV/c)

$8 \leq \Delta^2/\mu^2 \leq 25.5$

FIG. 1



$\pi^+ + d \rightarrow p + p +$ (neutrals)
(1.23 BeV/c)

FIG. 2

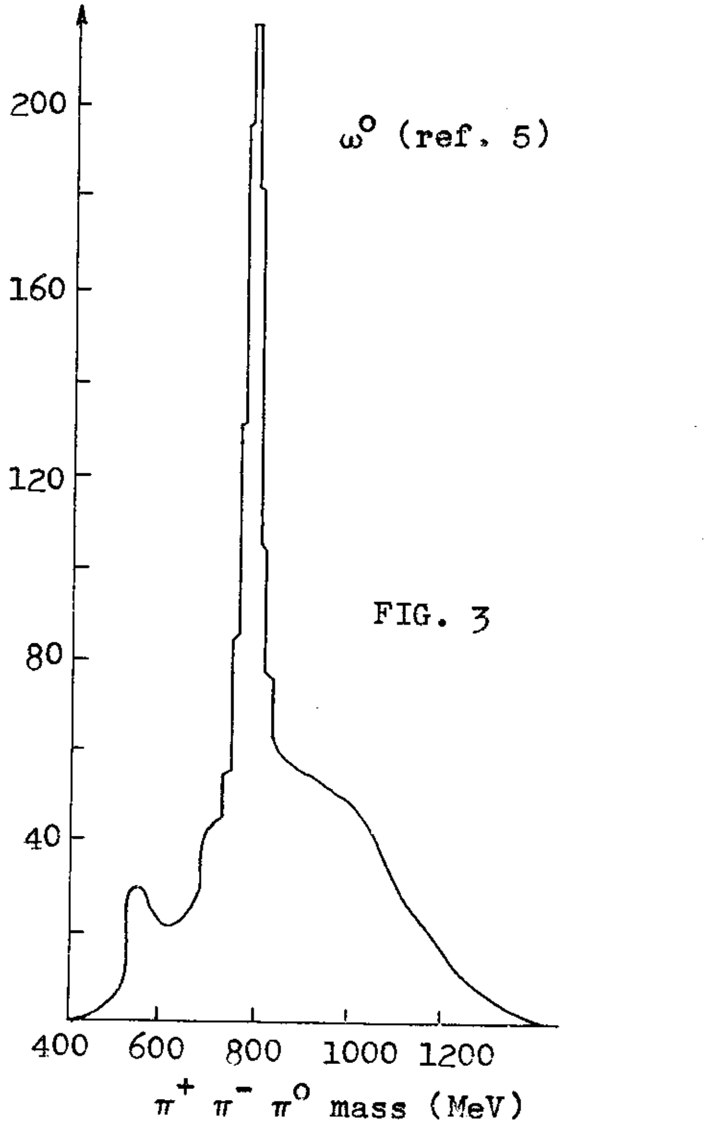


FIG. 3

$\pi^+ + p \rightarrow \pi^+ + p + \pi^+ + \pi^- + \pi^0$ (2.35→2.9 BeV/c)

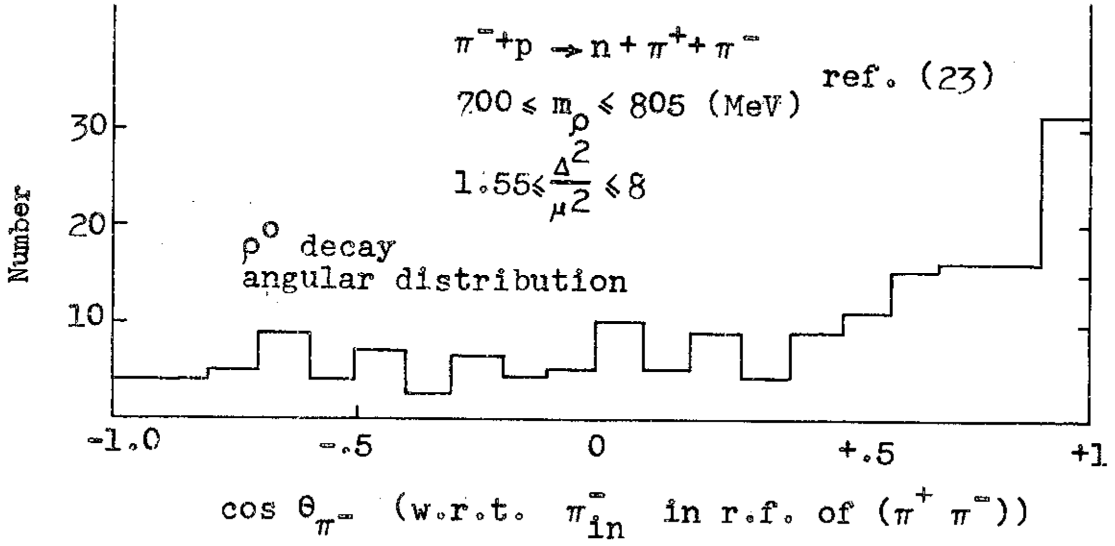

$\pi^- + p \rightarrow n + \pi^+ + \pi^-$
ref. (23)
$700 \leqslant m_\rho \leqslant 805$ (MeV)
$1.55 \leqslant \frac{\Delta^2}{\mu^2} \leqslant 8$
ρ^0 decay
angular distribution
Number
30
20
10
-1.0
-.5
0
+.5
+1
$\cos\theta_{\pi^-}$ (w.r.t. π^-_{in} in r.f. of $(\pi^+\pi^-)$)

FIG. 4

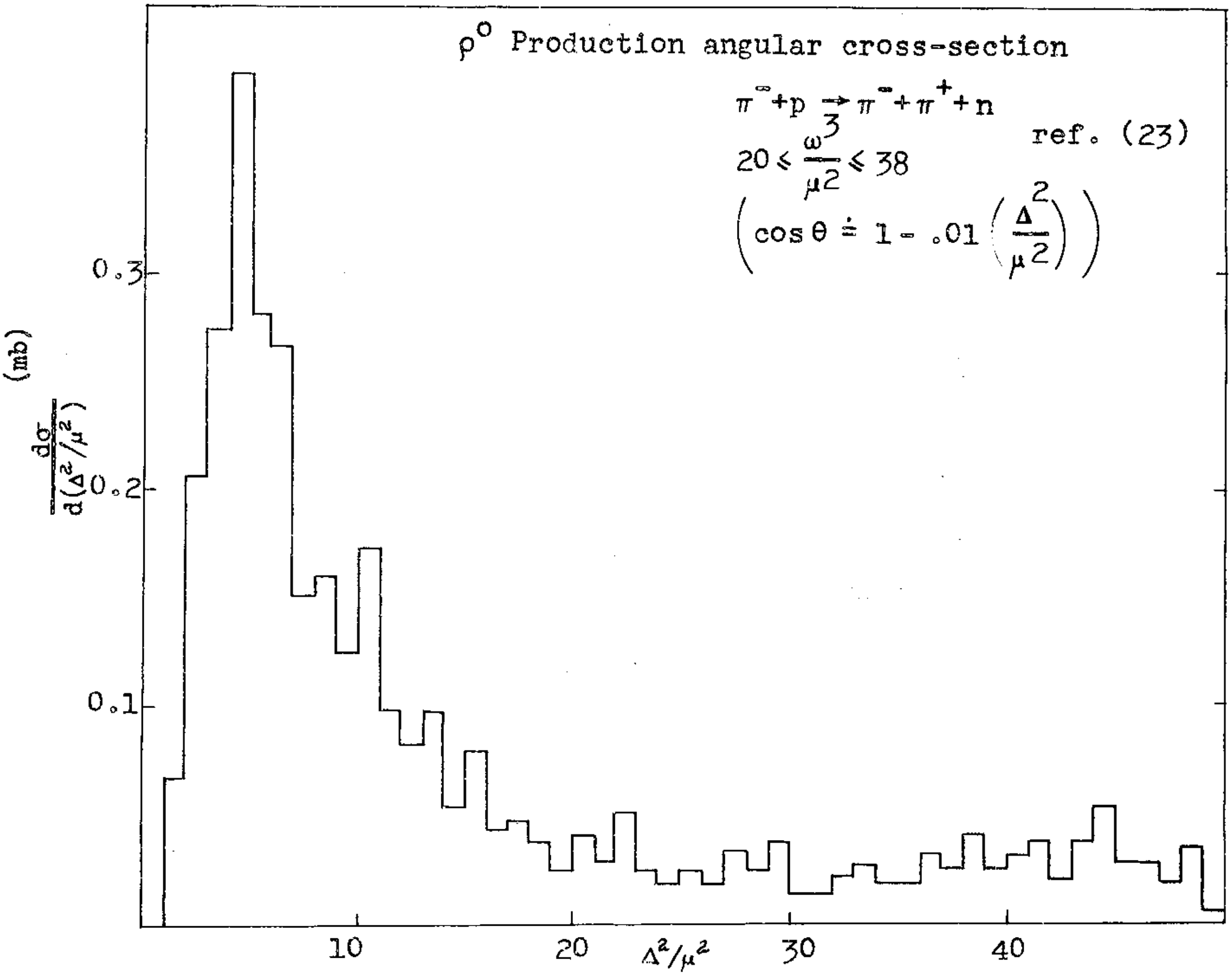
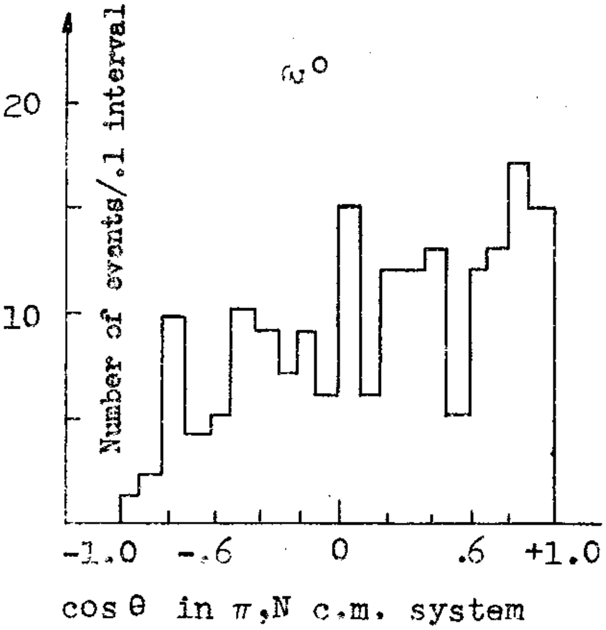

ρ^0 Production angular cross-section
$\pi^- + p \rightarrow \pi^- + \pi^+ + n$
ref. (23)
$20 \leqslant \frac{\omega^3}{\mu^2} \leqslant 38$
$\left(\cos\theta \doteq 1 - .01\left(\frac{\Delta^2}{\mu^2}\right)\right)$
$\frac{d\sigma}{d(\Delta^2/\mu^2)}$ (mb)
0.3
0.2
0.1
10
20
30
40
Δ^2/μ^2

FIG. 5

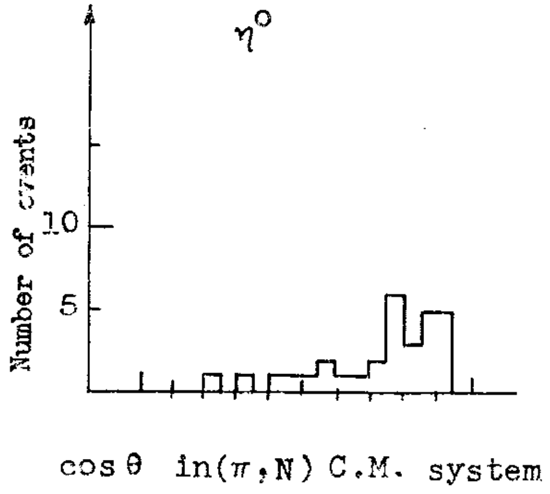
Production Angular Distributions



$\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + \pi^0$
(1.23 Bev/c)
$740 \leqslant m_\omega \leqslant 820$ MeV
ref. 15
182 events

θ is angle between π^+in, $\begin{Bmatrix}\omega^0 \\ \eta^0\end{Bmatrix}$

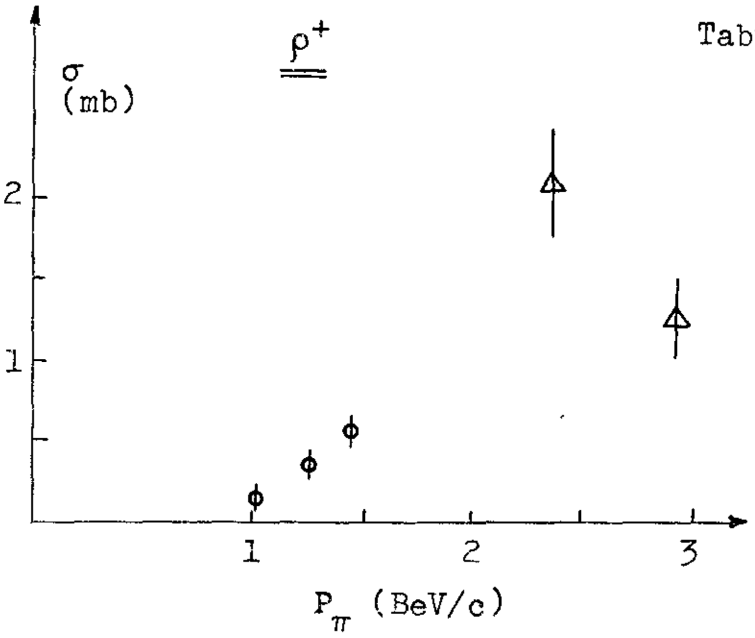
FIG. 6



$\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + \pi^0$
(1.23 BeV/c)
$520 \leqslant m_\eta \leqslant 560$
ref. 15
30 events

FIG. 7

Tabulation of Cross-sections for Production

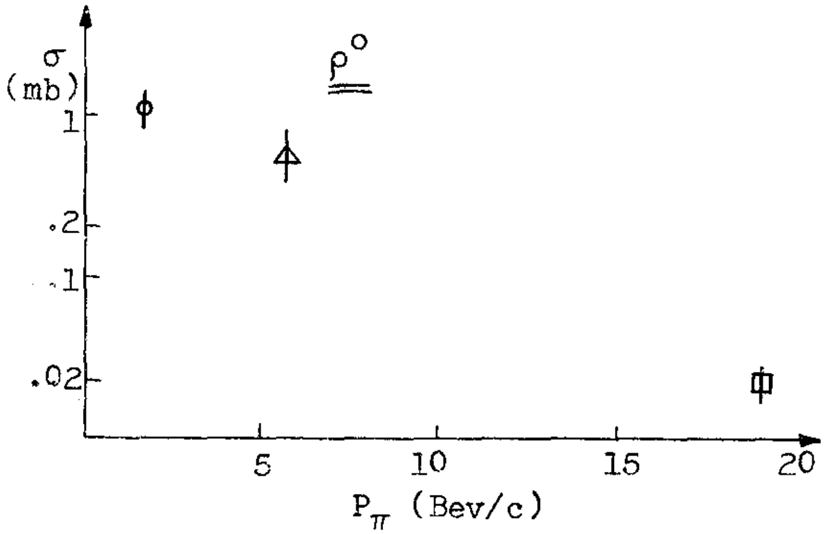


$\pi^+ + p \rightarrow (\pi^+ + \pi^0) + p$

o ⇒ (2)

Δ ⇒ (5)

FIG. 8



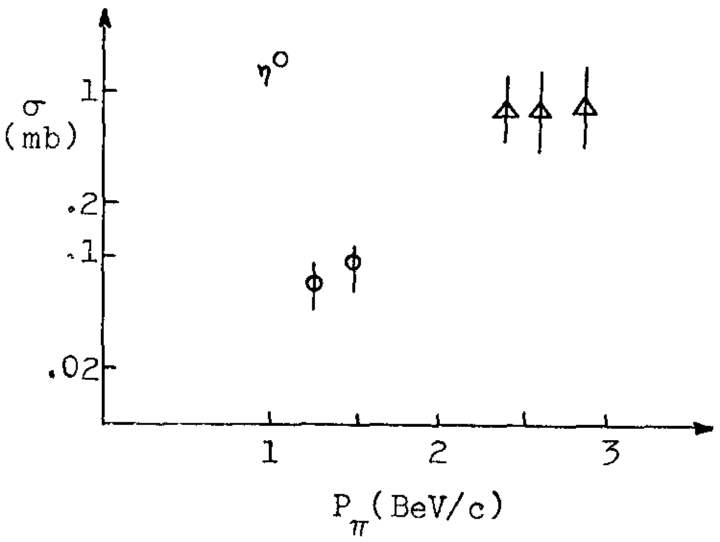
$\pi^- + p \rightarrow (\pi^+ + \pi^-) + n$

o ⇒ (23)

Δ ⇒ (19)

□ ⇒ (20)

FIG. 9

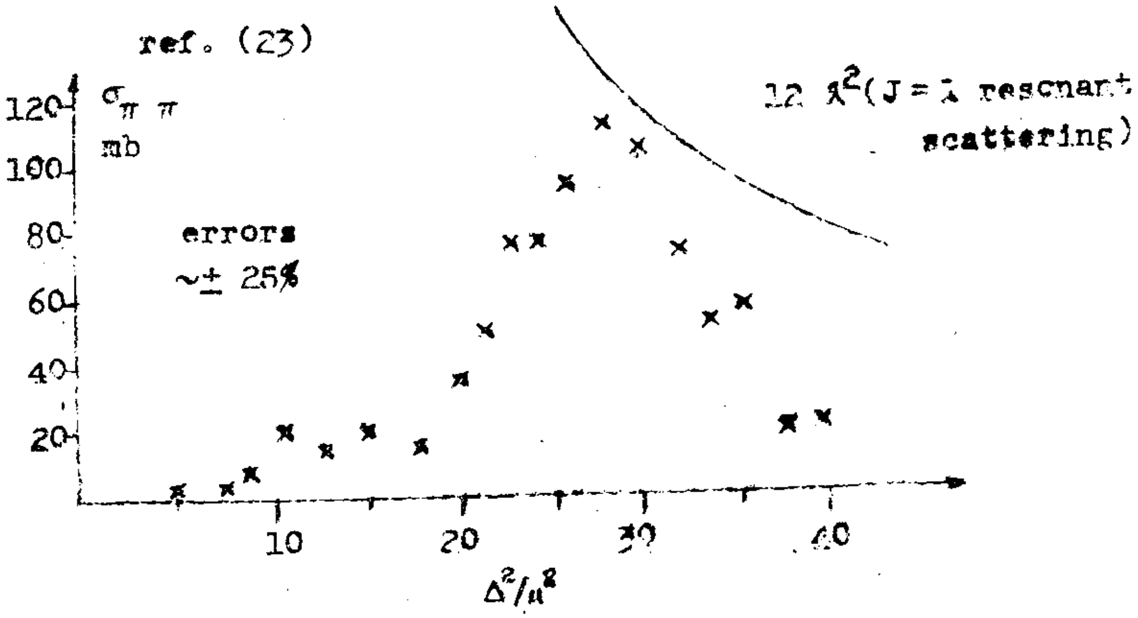


$\pi^+ + p \rightarrow (\pi^+ + \pi^- + \pi^0) + \pi^+ + p$

o ⇒ (2)

Δ ⇒ (5)

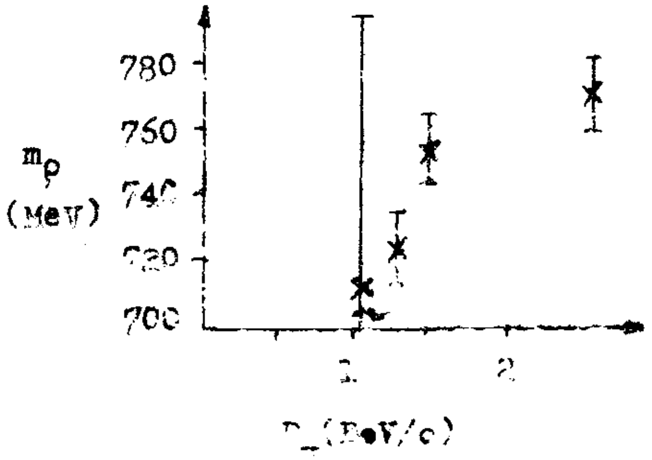
FIG. 10



$\pi^+\pi^-$ scattering cross-section (from Selleri$^{(50)}$ formula)

ref. (23)

FIG. 11



ρ^+ mass as a function of incident π^+ momentum $\pi^+ + p \to \pi^+ + \pi^0 + p$

FIG. 12

Theoretical-Considerations on the Pion Resonances

F. Demay

The last two years have seen a great success of the theoreticians, namely the discovery of the so called pion resonances. These had been foreseen and predicted to explain two important features of the physics of elementary particles.

On the one hand, in 1955 to explain the rise of the total cross section in the scattering of π^- by protons at 900 MeV, Dyson [52] and Clark [53] independently introduced the idea of a strong $\pi - \pi$ interaction. Cool, Piccioni and Clark [54] tried to explain their experimental results with the help of this resonant state.

On the other hand the study of the electromagnetic structure of the nucleon led to some difficulties in explaining the values of the form factors. To remove these difficulties Nambu [55] considered the possibility of the existence of a heavy neutral vector meson, with isospin zero and mass two or three times that of the ordinary pion, and called it ρ.

The electromagnetic properties of the nucleon had been studied by dispersion relation methods. It was successful in accounting for the isotopic vector properties of the nucleon but was unnable to explain simultaneously the value of the magnetic moment distributions. For this reason Frazer and Fulco [56] included a strong $\pi - \pi$ interaction in a P-wave state.

However it was not understood why the radius of the isotopic scalar charge distribution was nearly the same as that of the isovector charge. So Chew[57] tried to explain the situation by the existence of a 3π resonance or bound state. A synthesis of these ideas was made by Fubini et al[58] who showed that the 2 resonances (2π and 3π) were not sufficient to explain completely the structure of the nucleon.

An extensive application of ω and ρ to the calculation of the form factors of the nucleon is due to Gell-Mann and Zachariasen[60].

Independently Sakurai[59] in a general theory of strong interactions predicted the existence of a $T = 1$ vector meson (P-wave, 2π) and two $T = 0$ vector mesons ($J = 1, 3\pi$ resonance).

All these resonances and many more have been discovered and used to explain the facts which where at the origin of their prediction but they created new problems which we will briefly review.

The most important of these problems are the calculation of the mass and width of the resonances and the determination of the modes of decay and their corresponding branching ratios. One major part of the problem is the role of the electromagnetic effects in the decay of η. Finally these resonances have been very useful to explain some features of the decay of τ and τ'.

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Report on non Baryonic Resonances - Strange Isobars

A. L. L. Videira

We intend to summarize the properties of resonant states with quantum numbers $B=0$, $S\neq 0$, obtained in strong interactions.

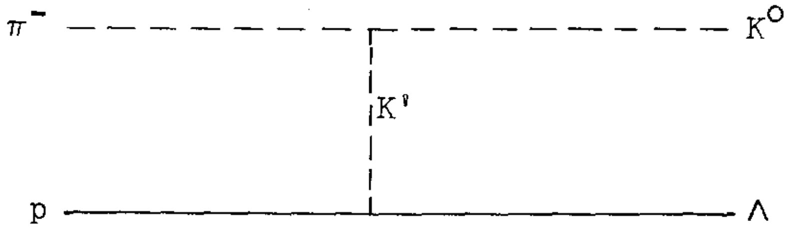
Following B. P. Gregory[1] we divide this presentation in two parts: one listing the well established isobars, and the other listing possible new resonant states.

1) The K^*

The first suggestion of a resonant state in the K system (K') was made by Tiomno et al. and Gell-Mann[2] on completely different grounds. Gell-Mann suspected the existence of the K^* from the theory of weak interactions. He concluded for the possible existence of two new scalar mesons: $0^+(\sigma)$ and $0^-(K')$. Tiomno et al. tried to explain the backwards peaked angular distribution (C.M.) of the Λ in the reaction

$$p+\pi^- \longrightarrow K^0+\Lambda \qquad (1)$$

by assuming that the production was dominated by a graph of the type



The possibility of the existence of this K' would avoid Pais explanation [3] of the Λ angular distribution based on a $KK\pi$ interaction, supposing opposite parities for K^+ and K^o, with its consequences of failure of charge independence of the π interaction [4].

Soon afterwards the resonance was found by Alston et al [5].

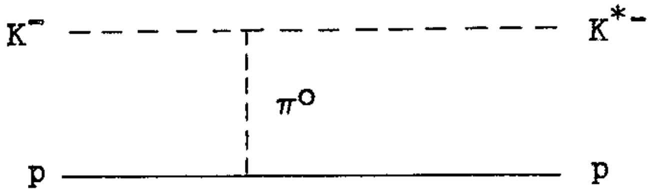
While in (1) a scalar K^* was suggested, some papers indicated a vector resonance and M. Schwartz [7] proposed a method to determine $J(K^*)$ in $p + p \longrightarrow K^o + K^{*o}$ reactions (see below).

It was observed [8] that the simple picture of a K^* exchange term to explain the angular distribution was incomplete, since it predicted no polarization for the Λ's in contrast with the large polarization found experimentally.

Several authors [6] investigated the reaction

$$K^- + p \longrightarrow K^{*-} + p \qquad (2)$$

assuming that it is produced mainly through the exchange of a single pion (OPE)



To explain some of the experimental results which disagreed with the predictions of the OPE model, MacDowell et al [9] proposed a modification, assuming that K^* production is dominated by the

Y* at 1815 MeV ($D^{3/2}$) together with the π exchange term and assigning spin one to the K^*. Ball and Frazer [10] and others also related dynamically this Y^* (1815 MeV, $D^{3/2}$) to the K^* with spin one.

Production: It was produced with $K^{\pm}$ or π^- and p in hydrogen or propane bubble chambers, according to the reactions

$$K^+ + p \rightarrow K^{*+} + N^+ \quad (\text{or } K + N^* \rightarrow K^* + N^*) \tag{3}$$

$$K^- + p \rightarrow K^{*\overset{0}{-}} + N^{\overset{0}{+}} \quad (\text{or } K + N^*) \tag{4}$$

$$\pi^- + p \rightarrow K^{*0} + Y^0 \quad (\text{or } K + Y^*) \tag{5}$$

$$\bar{p}_{\text{stopped}} + p \rightarrow K^{*\overset{+}{\underset{-}{0}}} + K + \pi \tag{6}$$

The reactions in parenthesis are competitive modes of production; the N^*_{33} resonance appears abundantly in the $K^+ + p$ reactions [21, 23] (they may play an important role due to interference effects). The $K^- + p$ reactions produce also Y^*.

Mass and Width: Table I summarizes the results on mass and width of various groups. They indicate a value of approximately 890 MeV for the mass and a width of about 50 MeV, in contradistinction to 16 MeV first repported [11].

Isospin: To determine the isospin of the K^* let us consider the ratio

$$R = \frac{K^{*-} \longrightarrow K^- + \pi^0}{K^{*-} \longrightarrow \bar{K}^0 + \pi^-}$$

assuming the K meson to form an isodoublet. If we assign I(K*) = 1/2 we obtain R = 1/2; if I(K*) = 3/2 we get R = 2. Alston et al. [5] measured $R_{\text{exp}} = 0.75 \pm 0.35$, strongly suggesting T = 1/2;

Incident particle	Momentum in $\frac{\text{GeV}}{c}$	Mass	Width	Reference	Authors
K^-	1.15	885	16	5	M.H.Alston et al (Berkeley)
	1.22	890	47	12	
	1.47	890	60	13	A. Cooper et al CERN Amsterdam, Glasgow
	2.24 2.44	900	$\leqslant 40$	14	L. Bertanza et al (Berkeley)
π^-	2.03 2.15	880	60	16	G. Alexander et al (Berkeley)
	1.55- -2.35	885	60		
	2.0	898	60	17	D. Colley et al (Columbia, Rutgers)
	2.17 2.25	885	50	18	G.A. Smith et al (Berkeley)
	1.89	≈ 875	> 40	19	A.R.Erwin et al (Wisconsin Brookhaven)
	2.1	≈ 880	≈ 40	20	R.H.March et al (Wisconsin, Brookhaven)
K^+	1.45	900	60	21	G.B.Chadwick et al (Oxford, Paduc)
	1.96	890	60	22 23	W.Chinowsky et al (Berkeley)
$\bar{p}$		885	55	24	R. Armenteros et al (CERN, Paris)

also March et al.[20], Alexander et al [15], Chinowsky et al [22] indicate that $I(K^*) = 1/2$ is most certain [28].

Spin: There is some conflicting evidence concerning the K^* spin [25]

Evidence for $J(K^*) = 0$:

In their paper anouncing the discovery of the K^*, Alston et al [5] considered the reaction

$$\begin{array}{ll} K^- + p \rightarrow K^{*-} + p & (a) \\ \quad\quad\quad\quad \hookrightarrow \overline{K^0} + \pi^- & (b) \end{array} \qquad (7)$$

They found that the angular distribution for (a) is consistent with isotropy. Assuming that S-wave production dominates this reaction, which seems reasonable since the energy studied (incident K^-'s of 1.15 BeV/c, $E_{c.m.} = 1863$ MeV) is very close to the threshold ($E_{c.m.} = 1823$ MeV) and the distribution is isotropic, they could exclude spin assignments higher than one; but they could not distinguish between 0 and 1. To investigate properties of the K^* in more detail these authors studied the above reaction with K^-'s of incident momentum 1.22 BeV/c ($E_{c.m.} = 1895$ MeV) [12]. The proton C.M. angular distribution for the K^* events shows a complicated pattern, indicating that partial waves higher than S-waves contribute to the reaction, and ruling out the OPE diagram (aparently $\cos^4$ terms are necessary to fit the data).

The production and decay of the K^* can be characterized by 3 angles: the production angle, and the polar and azimuthal decay angles. In practice, it is more convenient to use the following decay angles: the Adair angle, the angle made by the decay $\overline{K}^o$ with the normal to the production plane, and the angle made by the decay $\overline{K}^o$ with the direction of the K^*. For $J(K^*)=0$ all three angular distributions must be isotropic. For $J(K^*)=1$ the distributions can vary from $\sin^2$ to $\cos^2$ in any of the 3 angles above. Their results are the following:

a) all the distributions are consistent with isotropy;

b) there is no obvious deviation from the simple two body production model $K^- + p \rightarrow K^{*-} + p$, followed by the decay $K^{*-} \rightarrow \overline{K}^o + \pi^-$.

The isotropy does give strong support to the assignment $J(K^*) = 0$. A vector K^*, however, is not inconsistent with an isotropic distribution, since if higher partial waves contribute to the effect they could cause the decay distributions to vary rapidly with the production angle.

Evidence for $J(K^*) = 1$:

A) Armenteros et al [24] studied the K^* looking at $\overline{p}p$ annihilations at rest in the reaction

$$\overline{p} + p \rightarrow K_1^o + K^{*o} \qquad (8)$$

Their angular distribution of the decay products in the K^* rest system is quite consistent with isotropy, and hence they cannot get any conclusion from there. M. Schwartz has proposed [7] a method to obtain $J(K^*)$ from reaction (8) above, assuming S-wave $\overline{p}$-p capture predominates. If $J(K^*)=0$, $P(K^*)=1$, reaction (8) cannot be produced in the $^3S_1$ state by P conservation: P of the initial state is odd, $P(\overline{p}p) = (-1)(1)$, while that of the final state is even, $P = (-1)^{\ell+1}$, where ℓ, the relative angular momentum between the K and K*, must be 1 (for angular momentum conservation). P conservation allows (8) to be produced in the $^1S_0$ state, which is even under charge conjugation, and hence the final state must consist either of $K_1^o K_1^o \pi^o$ or $K_2^o K_2^o \pi^o$ (and also of $K^+\pi^\mp$), but not of $K_1^o K_2^o \pi^o$. If $J(K^*) = 1$, reaction (8) can proceed both from the $^1S_0$ and $^3S_1$ states, and in this case the final state will be an incoherent mixture of $K_1^o K_1^o \pi^o$ (or $K_2^o K_2^o \pi^o$) and $K_1^o K_2^o \pi^o$.

They obtain strong evidence that S-wave capture predominates in the $\bar{p} + p \rightarrow \overline{K^o} + K^o$ reaction, and furthermore that the number of events corresponding to (8) and leading to a final state $K_1^o K_2^o \pi^o$ is 36.5 ± 15. If one extends the S-wave capture argument to all inelastic channels, including thus, $\bar{p} + p \rightarrow K + \bar{K}^*$, these data are not compatible with spin zero.

B) Chinowsky et al.[23]. The production of K^* in

$$K^+ + p \rightarrow K^* + N_{33}^* \qquad (9)$$

at 1.96 BeV/c permitted them to identify the K^* as a vector meson. Following the Adair analysis they examined the distribution in the angle α between the outgoing K^+ in the K^* C.M. system and the incident K^+ direction. They found strong anisotropy which can be fitted with $\cos^2 \alpha$ and hence, since Alston et al [5] indicated that $J(K^*) < 2$, they concluded by $J(K^*) = 1$ and $P(KK^*) = 1$. For $P(K\Lambda N) = -1$ this implies $J(K^*) = 1^-$.

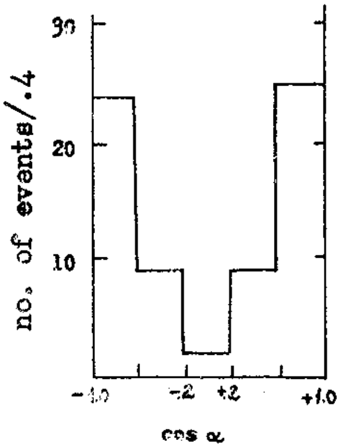


FIG. 3

C) Smith et al. [18]. They give further evidence for $J(K^*) = 1$, based on a spin-alignment effect as observed in the reaction

$$\pi^- + p \rightarrow \Sigma^0 + K^{*0} \qquad (10)$$

In an ateempt to observe K^* spin-alignment effects they plotted 3 angles α, β, γ which define a set of direction cosines in the K^* rest frame. Fig. 4 shows the experimental distributions in the angles. They conclude also for $J(K^*) = 1^-$.

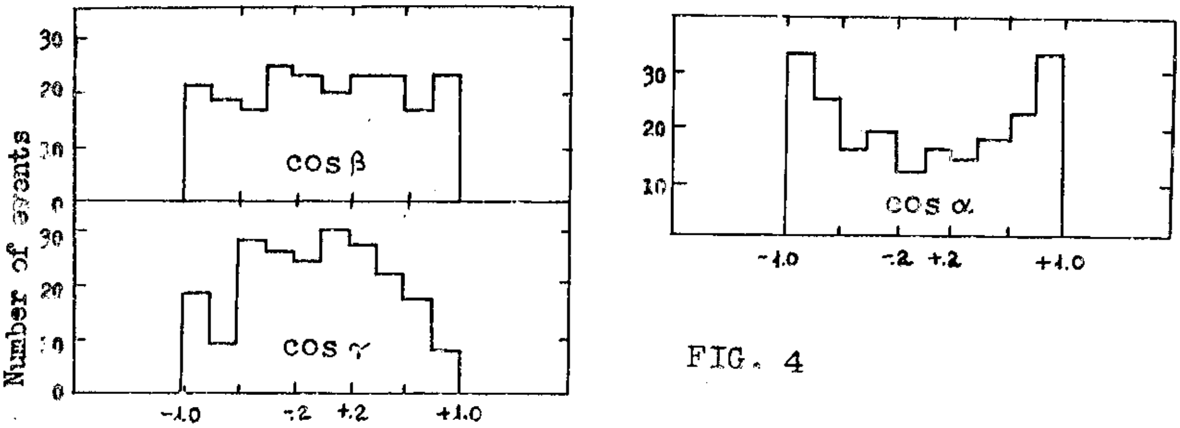
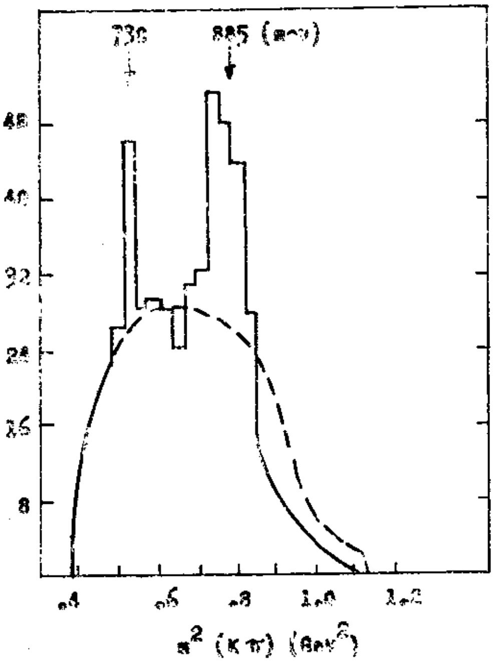


FIG. 4

Cross-Section:

In the paper where they anounced the K^*, Alston et al presented a total cross section for $\overline{K^0}\,\pi^-$ production of (2.0 ± 0.3) mb. From a total number of 48 $\overline{K^0}\,\pi^-$ events, they classified 21 as coming from the decay of the K^*. Hence, the cross section for reaction (7-A), assuming $I\,(K^*) = 1/2$, was (1.3 ± 0.3) mb. In (12) they indicate instead, a total $K^{*-}p$ cross section of (1.8 ± 0.4) mb.



K^- mass-squared distribution for Σ^-, Σ^0, Λ^0 events at incident-pion momenta of 1.80 - 2.94 BeV/c.

2. Possible other strange resonant states.

There have been reports on other "bumps" appearing in associated production reactions. Their existence is not well established, however, either because of the poor statistics or because its single appearance has not been reproduced in independent evidences.

a) The K^* 730

There is only one report [15, 16] of this resonance, but quite strong: "the statistical significance of this peak above the background is estimated to nearly 3 standard deviations" according to the authors. Many groups have looked for this 730 K^*. We list them below together with their findings.

i) Alexander et al [15, 16]. They looked at

$$\pi^- + p \rightarrow \begin{cases} \Sigma^- + K^0 + \pi^+ \\ \Sigma^- + K^+ + \pi^0 \\ \Sigma^0 + K^+ + \pi^- \end{cases} \qquad (11)$$

with π^-'s of 2.1 BeV/c [15], and in the range 1.55 - 2.35 BeV/c [16]. They give evidence of a sharp peak at 730 MeV, $\Gamma = 20$ MeV. They propose the following quantum numbers: $I = 1/2$, suggested by the absence of any effect in the $\Sigma^+ \pi^- K^0$ events; $J \geqslant 1$.

(see figure in the preceding page)

ii) March et al. [20]. They also studied associated productions reactions induced by π's:

$$\pi^- + p \rightarrow \Sigma + K + \pi \, , \qquad p_\pi = 2.1 \text{ BeV/c}$$

(They did not find any evidence that the Λ is produced in association with a K^*).

Comparing their data with those of Alexander et al., obtained almost under identical conditions, we find the agreement between the two experiments except in two points. March et al.

find a smaller width for the K^* (see Table I), and although their events show a peak at the identical mass values, it is not statistically convincing (their previous data at 1.96 BeV/c presents also a small bump with the correct mass [19]).

iii) Alston et al [12]. Their data show that the K^* 730 does not play any significant part in reaction $K^- + p \rightarrow \overline{K^0} + \pi^- + p$. The data are consistent with zero cross section for the production of this resonance; they have, however, a slight excess of events between 720 and 730 MeV. If this is interpreted as due to this new resonance, then the cross section has the upper limit of 37 μb.

iv) Colley et al [17]. They did not see any evidence in

$$\pi^- + p \longrightarrow \Sigma(\text{or } \Lambda) + \pi + K, \quad p_\pi = 2.0 \text{ BeV/c},$$

which are the same reactions, at the same energy where Alexander et al. found it.

(24) They did not find any evidence in $p + p \rightarrow K^0 + K^{*0}$

v) Armenteros et al.

vi) Cooper et al [13]. They did not find any evidence in $K^- + p \longrightarrow p + K^{*-}$.

b) $K\overline{K}$ interaction

The first report of an enhancement in the number of events of the $K\overline{K}$ system was given by Erwin et al. [26]. This evidence was also presented at the CERN Conference (1962) [27]. They studied

$$\left.\begin{array}{l}\pi^- + p \rightarrow K_1^o + K_1^o + n \\ \qquad\;\; \rightarrow K^o + K^- + p\end{array}\right\} , \; p_\pi = 2.0 \text{ BeV/c.}$$

For π^-'s of much higher energy (and for K_1^o K_1^o modes of decay) similar evidence was presented at that Conference [28, 29, 30]. Bingham et al [28] find that the relative energy, Q_{KK}, of the two K^o's in $K\overline{K}$ production tends to be quite small ($Q_{KK} = \sqrt{(E_{K_1} + E_{K_2})^2 + (p_{K_1} + p_{K_2})^2} - 2m_K$). Moreover, their Q_{KK} distribution seems independent of available C.M. energy (i.e. beam momentum). This apparent independence of Q_{KK} from the production kinematics is evidence of a strong correlation between the K^o's of $K^o\overline{K^o}$ pairs. It is possible to attribute this correlation to a low energy $K\overline{K}$ interaction or to a resonant state of mass ~1.1 BeV, which could decay into a K_1^o K_1^o pair.

Bigi et al [29] and Belyakov et al [30] compared the effective mass distribution to a curve computed by a Monte Carlo method combining K's from different events. A significant increase in the number of K_1^o K_1^o events of effective mass below 1200 MeV is observed although the existence of a peak cannot be definitely proved.

Bertanza et al.[14, 31] looked at the reactions

$$\left.\begin{array}{l}K^- + p \rightarrow \Lambda + K^o + \overline{K^o} \\ \qquad\;\; \rightarrow \Lambda + K^+ + K^-\end{array}\right\} , \; p_K = 2.24 \text{ and } 2.5 \text{ BeV/c.}$$

They presented a histogram of 37 events comprising a small number of observed K_1^o K_1^o events (3) and about the same number of

K_1^0 (K_2^0 or K_1^0) and $K^+ + K^-$ events. A strong enhancement is seen in the Q_{KK} value region between 0 and 100 MeV. After subtracting the phase space contribution they plot the effective mass * distribution, $M_{eff}(K\bar{K})$, from which they take $m_{K^*=K\bar{K}} = 1020$ MeV, $\Gamma = 20$ MeV.

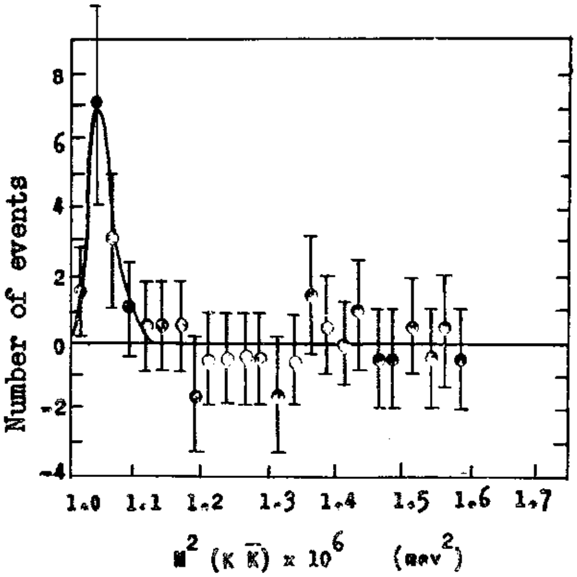


FIG. 5

Since the departure from phase space occurs so near to the threshold there is the possibility that the enhancement effect is due to S-wave final-state interaction between the K and $\bar{K}$.

Finally, this effect is not observed for either $K_1^0 K_1^0$ or $K^+ K^-$ events produced by stopped anti-protons in the reaction $\bar{p} + p \rightarrow K + \bar{K} + \omega^0$ [32].

Possible quantum numbers assignment to the $K\bar{K}$ system:

a) Sakurai [33]: If $K\bar{K}$ (I = 0) is due to S-wave $K\bar{K}$ pairs, then it is forbidden to decay into $K_1^0 K_2^0$. In this case it would be the same thing seen by Erwin et al. in $\pi^- + p \rightarrow K^0 + \overline{K^0} + n$.

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* For all possible reaction channels, effective mass distributions are defined by $M_{eff} = \left[(\Sigma E_i)^2 - (\Sigma p_i)^2\right]^{1/2}$.

$$I = 0,\ J = 0 \Longrightarrow G = (-1)^{I+J} = +1 .$$

If $K\bar{K}$ $(I = 0)$ is due to P-wave $K\bar{K}$ pairs, then it is forbidden to decay into $K_1^0 + K_1^0$. In this case $I = 0$, $J = 1 \Longrightarrow G = -1$, and hence forbidden to decay into two pions. This last possibility allows the interpretation of the effect as the decay of an ω-like $I = 0$, $G = -1$, vector meson. Fast decay into 3π is then allowed.

b) Gatto [34]: He looks for a quantum number assignment for $K\bar{K}$ that strictly forbids decay into 2π and 3π and makes 4π decay very slow. For $I = 0$, $J < 2$ we have an unique assignment satisfying these requirements: $J = 0$, $P = +1$, $G = -1$. Then

decay into 2π is strictly forbidden by C
" " 3π " " " " P
" " 4π " slowed down " G (goes only electro-magnetically)
" " K^+K^-, $K_1^0\ K_1^0$, $K_2^0\ K_2^0$ is strictly forbidden by C. The only decay mode is $K_1^0K_2^0$ (through violation of G).

c) Minami, Huggett [35]: $I = J = 1$ and $I = 0$, $J = I$ (same quantum numbers as the ρ and ω, respectively). They claim both these assignments are unlikely because there seems to be no evidence for the peak due to a strong interaction of $J = 1$ states in 2π or 3π systems in the neighborhood of 1020 MeV. The only peak observed in this region is that from the resonance corresponding to the 2π system of mass 1040 MeV $(J = 2?)$.

$I = J = 0$ would imply fast decay into 2π. Dismissed in the same ground.

Finally, we have the assignment $I = 1$, $J = 0 \Longrightarrow G = -1$, which would suggest fast decay into 3π (forbidden because of P and total angular momentum conservation. Thus the possible modes would be into 5π and $\eta + \pi$ (if η: 0^{-+})).

c) Multipion Resonances

Belyakov et al [30] studied 2, 3 and 4 particle resonances in $\pi^- p$ reactions with a 24 propane bubble chamber exposed in 7 - 8 BeV/c beam at Dubna. Among many other combinations they calculated the effective masses of the following ones

$$K^0\pi,\ K^0 2\pi,\ K^0 3\pi$$

In the distribution of effective masses for the combination $K^0 \pi^+ \pi^- \pi^\pm$ (K^{***}) they find two maxima, one 1.4 BeV and the other at 1.63 BeV. They interpret as a resonance only the higher one, claiming that the number of events at 1.4 BeV is too small. This K^{***} would possibly decay in the channels

$$\begin{aligned} K^{***} &\to xK^* + 2\pi \\ &\to K^* + p \\ &\to K + \pi + p \end{aligned}$$

They searched also for resonances in $K^0 \pi^\pm \pi^\pm$ (charge 2) and $K^0 \pi^+ \pi^-$ (charge 0) as well. They found a peak in the region 1.1 - 1.2 BeV in the distribution of $K^0 \pi^\pm \pi^\pm$ (K^{**}).

So they have:

$$K^{***} \simeq 1650 \text{ MeV}$$
$$K^{**} \simeq 1150 \text{ MeV}$$

In the other hand their data show very poor maxima at an energy coinciding with that of the K^*.

* * *

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