THE FORMATION OF HIGH MASS MESONS

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The progress in our understanding of the formation of high mass mesons appears to be very slow, since we still await a clearly identified state, although we have structures in cross-sections, and new results in certain channels look very promising.

In Part I of this review, a brief introduction is given to nucleon-antinucleon formation. Part II covers the total cross-section, both the measurements and attempts to interpret the structure; Part III includes new data on charge exchange; and elastic scattering is reviewed in Part IV. Part V on annihilation into two mesons has new data and analyses. In Part VI, some states which have not been confirmed are listed for completeness, and Part VII gives the conclusions and future outlook.

1 Introduction

The state of the art in meson spectroscopy was summarised, after the 1974 Meson Conference at Boston, as 12+4 established states, with 51 'effects' registered with the Particle Data Group. A reason, most often given for the small number of established mesons, is the absence of a laboratory target on which to form them.

(a) Nucleon antinucleon interactions provide the only way to form mesons in the laboratory, with the exception of $e^+e^-$ collisions which couple exclusively to $1^-$ states.

(b) There are the obvious quantum number restrictions, namely $S = 0$, $L = 0$ or 1 and the mass must be greater and 2 nucleon masses.

(c) The mass resolution of formation experiments is potentially good, e.g. a 1% uncertainty in $\Delta p/p$ at 1.33 GeV/c (mass = 2194 MeV) implies an uncertainty of 4.6 MeV in $\Delta M$. However there are disadvantages since a state at 1.33 GeV/c, which is 200 MeV wide, will spread its 'effects' from 1.03 to 1.6 GeV/c. This could make life difficult if we are looking for broad states which overlap.
(d) We can form a rich spectrum of $J^{PC}$ states. Using a simple $L$-excitation model for $\bar{\Lambda}N$ we have the same states as with $\bar{q}q$. $(P = (-1)^{L+1}, C = (-1)^{L+S})$.

- Singlet $\bar{\Lambda}N$ feeds $0^{-}, 1^{+}, 2^{++}, 3^{++}, \ldots$.
- Triplet $\bar{\Lambda}N$ ($L = J$) feeds $1^{++}, 2^{--}, 3^{++}, 4^{--}, \ldots$.
- Triplet $\bar{\Lambda}N$ ($L = J \pm 1$) feeds $0^{++}, 1^{--}, 2^{++}, 3^{--}, 4^{--}, \ldots$.

In this model exotics of the second kind are excluded, i.e. natural parity states cannot have unnatural $C$. Some final states select a particular series, e.g. in $\pi\pi$, and $kk$ parity conservation ensures natural parity only. All the above states are nonets with $I = 0$, and 1 members.

(e) What $L$ values can we excite? Figure 1 compares the situation in $\bar{\Lambda}N$ and $\pi\Lambda$ formation experiments if resonances are excited with a simple impact parameter: radius of $\sim 1$ fm. In $\pi\Lambda$ the states on the leading $N^*$ and $\Delta$ trajectory are easily reached. In $\bar{\Lambda}N$ the leading meson trajectory cannot be excited, and it would seem that we may be hunting for daughters with two units of angular momentum less than the leading states.

The possible decay of a high spin meson into $\bar{\Lambda}N$ is considerably suppressed by angular momentum barrier effects and phase space; light particles are favoured. In Table 1, the factors are presented for the case of a state with $J = 5$ and a mass $\sim 2.18$ GeV near the leading meson trajectory - and for a state $J = 3$ with the same mass. The angular momentum factor $B_k$ is evaluated using the formalism of von Hippel and Quigg (1). It is clear that for high spin the coupling to $\bar{\Lambda}N$ is very much suppressed compared with that of $\pi\pi$.

These simple angular momentum considerations, based on a radius of $\sim 1$ fm, if correct, make the study of meson spectroscopy via $\bar{\Lambda}N$ formation both interesting and difficult, since we may be trying to identify high mass, low spin mesons which are most probably broad.

## 11 Total Cross-sections

We have a precise knowledge of the $\bar{p}p$ total cross-section from two experiments at BNL. Abrams et al. (2) covered the range 1.0 to 3.3 GeV/$c$, and Carroll et al. (3) from 0.385 to 1.06 GeV/$c$. Figure 2 shows the data from 0.385 to 2.5 GeV/$c$; three small structures are evident: sitting on a large smooth background cross-section. In figure 3 the data from the low momentum experiment only is shown, where the new state at 1932 MeV is clearly evident.
Measurements of $\bar{p}p$ and $\bar{p}d$ cross-sections enable an $l$-spin analysis to be done using the relations

$$\sigma_p = \frac{1}{2}\sigma_0 + \frac{1}{2}\sigma_1$$
$$\sigma_n = \sigma_1$$
$$\sigma_d = \sigma_n + \sigma_0 - \sigma_1$$

Where $\sigma_0$ is the Glauber correction for shielding in the deuteron. At low momenta the analysis does not work. The appropriate form of $\sigma_0$ is not known and the Fermi smearing demands a knowledge of cross-sections at very low momenta where extrapolation of measured values yield unphysical results in the analysis. However Carrol, et al. performed the decomposition for several models of $\delta\sigma$, believing that structure in $l = 0$ or $l = 1$ would not be created or destroyed. They favour $l = 1$ for the low mass state, but emphasize this is uncertain. Table 2 gives the properties of four states yielded from the total cross-section work by fitting a sum of Breit-Wigner resonances and smooth background to the data. The "resonant" cross-sections are appreciable on an absolute scale e.g. 18 mb at $0.475\text{ GeV/c}$. The elasticity $\chi$ is given assuming a $J$ value close to that expected from the simple angular momentum considerations of section 1.

We clearly have structures, possibly with low elasticities. It is perhaps worth noting that in the $\pi N$ system in a similar mass range the structure in the total cross section is also not very marked and the elasticities of baryon resonances similar to those in Table 2.

There exist attempts to explain these bumps in terms of the onset of single pion production. In the most recent, Ma et al. (4) derive the $l = 0$ and $l = 1$ single pion production cross-sections from threshold to $2.9\text{ GeV/c}$, these are shown in figure 4. They then fit with a sum of a Breit-Wigner plus a polynomial, where the parameters of the Breit-Wigner are taken from Abrams et al. They conclude that:

(a) for $l = 0$, the inclusion of a state at $2375\text{ MeV}$ does not improve the fit
(b) for $l = 1$, the addition of a state at $2350\text{ MeV}$ improves the fit, and single pion production could account for $-25^{+8}_{-8}\%$ of the total cross-section structure

Efforts to explain the structure at $2190\text{ MeV}$ via single pion production (5) failed, and so it seems unlikely that the most obvious threshold effects can account for all the structure.

If the bumps in the total cross-section are due to resonances, then each may be dominated by a given set of quantum numbers. All bubble chamber groups appear to agree that there exists copious resonance production in NN reactions e.g. $\rho$, $f$, $\omega$, $k^*$ and to a lesser extent $\Lambda_2$ and $\phi$. If one
cen detect quasi two body final states which select the given set of quantum numbers perhaps one can become more sensitive to the 'resonant' cross-section. However, the analysis of Ma et al. (6) of \( \bar{p}p \) and \( \bar{p}d \) from 1.5 to 2.9 GeV/c suggests that quasi two body cross-sections e.g. \( \rho \pi \) or \( \omega \pi \) fall rapidly with increasing momentum. They also show that cross-sections for single resonance production with uncorrelated pions indicate a broad maximum around 2.0 GeV/c, and conjecture that the two effects in combination give some of the total cross-section structure at 1.85 GeV/c. Alspector et al. (7) using the Rutgers Annihilation Spectrometer (RAS) have studied the topological properties of the \( \bar{p}p \) total cross-section with great statistical precision. The mass spectrum was measured as a function of:

(a) non-peripheralism - i.e., the angle of the most forward charged particle, determined from a set of counters downstream of the hydrogen target. Four levels were measured \( \theta = 2.5^\circ, 5^\circ, 10^\circ, \) and \( 20^\circ \) with a resolution of \( \pm 1^\circ \).

(b) multiplicity - determined from 32 counters surrounding the target. The charged multiplicity is differentiated from 0 - 6 with the final bin having events with >7 charged particles.

The idea behind the experiment was that if high mass bosons on the leading trajectory could be formed in \( \bar{p}p \), then the most probable decay is via \( \pi \)-cascade leading to a high multiplicity and non peripheral signature for narrow states.

The data, summed over all multiplicity and non-peripheral bins is shown in figure 5. It has structure. They performed a linear extrapolation to zero degrees and compared their results for the \( \bar{p}p \) total cross-section with those of Abrams et al. Table 3 gives the resonant parameters obtained by Alspector et al. from their fits to the data of Abrams et al. and RAS. The agreement is remarkably good.

The findings and conclusions of the RAS experiment for \( \bar{p}p \) can be summarised as,

(i) broad structures at 2190 MeV and 2360 MeV are confirmed
(ii) the position and width of the structure is not affected by cuts on multiplicity or non-peripheralism, which suggests one is seeing a single broad structure and not the composite of several narrow states.
(iii) the multiplicity distribution suggests a sizeable elastic contribution to the bump cross-sections.
(iv) there is no evidence for narrow states in the mass range covered.
(v) a monte carlo simulation of the multiplicity distribution at 2190 MeV from \( \Delta \) production, does not agree with the measured data.

(vi) a similar study in the mass region of 2360 MeV suggests that \( \Delta \) production could account for 40% of the 'bump' cross-section.

The tentative conclusions that we can draw from all these studies of the total cross-sections and related measurements are as follows:

1. there exists structure which is not understood.

2. it is not convincingly a threshold effect - although this may be responsible in part for the structure at 2360 MeV.

3. we are not seeing the sum of narrow states; although the state at 1932 MeV is narrow itself.

4. the structure does not appear to be a single resonance with a unique set of quantum numbers.

5. we may be seeing the combined effect of many broad states which will have to be identified via a partial wave analysis.

III Charge Exchange

In the reaction \( \bar{p}p - \bar{\eta}n \) the t-channel is dominated by \( \pi \)-exchange and is free from diffraction, the u-channel exchange must be exotic with \( B = 2 \), consequently one expects and finds, a small backward cross-section. The s-channel may contain the effects of meson formation.

There are two electronic measurements of the total reaction cross-section between 1 and 3 GeV/\( c \), Bricman et al.\(^{(8)}\) and the recent publication of the final results of Cutts et al.\(^{(9)}\). Both electronic experiments are the same in principle. An antiproton beam is incident on a hydrogen target surrounded by veto counters to veto charged particles and \( \gamma \)-rays. Corrections have to be applied for the self vetoing of \( n \) and \( \bar{\eta} \) in the veto shield, and for the \( K_2^0 K_2^0 \) final state which is small. The experiment of Cutts et al. also used iron-scintillator sandwiches for \( \bar{\eta} \) detection and measured \( d\sigma/du \) for \( |u| \leq 0.06 \) GeV\(^2\). The statistical accuracy of both experiments is \( \pm 1\% \), but there are significant systematic uncertainties, e.g., the correction for \( \bar{\eta} \) detection in the veto shield.

Figure 6 shows the data along with bubble chamber measurements, including the recent results of Colebourne et al.\(^{(10)}\) at 1.13 GeV/\( c \). The data of Bricman et al. is represented by the solid line, which is the result of polynomial fit to their data, and the dotted lines represent the systematic
uncertainty. There is a disagreement in normalisation between the two counter experiments. Cutts et al. make the point that the following sum rule should hold:

\[ \sigma(\bar{p}p+n\bar{n}) + \sigma(\bar{p}p+n\bar{n}+n\bar{n}) + \sigma(\bar{p}p+\text{neutrons}) \leq \sigma(\bar{p}p+\text{neutrons})\]

and claim that the data of Bricman et al. exceed this rule. The data of Cutts et al. show structure in the cross section, whereas the experiment of Bricman et al. could not easily accommodate the structure predicted from the total cross-section results.

The bumps in the data of Cutts et al. are seen more clearly in figure 7 where the cross section has been multiplied by the laboratory momentum. The structures are centred at 1.25 GeV/\(c\) (2164 MeV) and 1.8 (2360 MeV), both close to the values found in the total cross section. One would like to see the results of a fit of the form of a Breit-Wigner plus background in order to get a better feel for the positions, widths, and significance of the bumps.

The backward cross-section (\(|u| < 0.06 \text{ GeV}^2\)) of Storer et al.\(^{(11)}\) shows backward peaks whose slopes increase with momentum. Their data agrees well with Colebourne et al. where it overlaps. They examine the shape of \(d\sigma/du\) in the momentum range 1.4 to 2.1 GeV/\(c\) and from fits of the form \(|P_J(\cos \theta_H)|^2\) find \(J\) values in the range 2-5. Fitting to this form implies an extreme model of a pure resonance contribution, with no background, which seems an unlikely situation. Storer et al. note that the backward cross-section in charge exchange has the same magnitude and \(s\)-dependence as the backward elastic cross-section, and since diffraction makes no contribution to the charge exchange they argue that it probably is not dominating the backward elastic. A comment on this observation is deferred until the elastic data is discussed in section IV.

The situation with regard to \(s\)-channel states does not appear to be very satisfactory in the charge exchange reaction since we have a disagreement between two accurate experiments. One would like to see the properties of the structure and its significance quantified.

IV Elastic Scattering

In the elastic scattering we have a lot of data, on the total elastic cross-section, differential cross-sections, and the energy dependence of the backward cross-section. Here, as in charge exchange, the \(t\)-channel may be meson exchange, the \(u\)-channel exchange must be exotic and the \(s\)-channel may contain meson formation. The main difference is that the forward direction is dominated by diffraction.
We can estimate the contribution that the structures in the total cross-section will make to the total elastic cross-section which is naively the first place to look for direct channel effects. Table 4 gives the estimated enhancements based on the elasticities derived from the assumed J-values. The effects are small. The data on the total elastic cross-section is shown in figure 8. Any structure will probably remain unseen as long as several different experiments, each with different systematic errors, have to be used to measure the momentum dependence. The systematic errors in measurements of the total elastic cross-section can be appreciable, since usually $\frac{d\sigma}{dt}$ is measured down to some minimum value of t and then an extrapolation is performed in order to estimate the missing cross-section, which can be 20-30%. The functional form of the extrapolation varies from experiment to experiment. Clearly the best way to look for the structure is to take the data from a single experiment spanning the momentum range, analyse each momentum in a consistent way and assume the systematic errors neither create nor destroy structure.

A preliminary analysis of the data of Eisenhandler et al. (12) gives the total elastic cross-section from 0.8 to 2.4 GeV/c determine from a single experiment which measured differential cross-sections $(-.95 \leq \cos \theta \leq .95)$ at 20 momenta with 100 thousand elastic events per momentum. The angular distributions were fitted to the form $\sum \Lambda^p \left\{ P^l \right\} (\cos \theta)$ where the order of fit was increased until the $\chi^2$ per degree of freedom was 1. The $\Lambda$ value required was plotted against momentum so that the data could be fitted by a consistent and smoothly increasing order of Legendre Polynomial. The total cross-section derived from these fits is shown in figure 9, the error bars do not represent the statistical uncertainty but represent the spread in cross-section when the order of fit is changed by plus or minus one unit. It is possible that we are seeing two structures. This is a preliminary result and one would like to see the significance of any structure quantified. Also, the process of producing a total cross-section using some other functional forms for extrapolating the angular distribution must be repeated, before drawing conclusions.

It is interesting that recent data from Cooper et al. (13) shown in figure 10 also claim tentative evidence for structure, so perhaps we are at last establishing effects in the elastic cross section which if they persist could be used to get information on possible J values and elasticities of Abrams bumps, assuming they are resonances.

In an attempt to enhance any direct channel effects the backward hemisphere and backward direction have been selected as hunting grounds, away from diffractive contributions. There certainly exists momentum
dependent structures in the backward direction but what they mean is open to discussion. The experiments of Cline et al. (14) and College de France (15) both show evidence for a bump with mass 1939 MeV and 1.63 MeV, if a simple Breit-Vignier resonance is assumed. The picture we have of the backward elastic cross-section is shown in figure 11. The question of whether the observed structure is due to direct channel states or the dips of diffraction pattern passing through 180° has been raised (16).

If we consider the dip at 0.9 GeV/\e and examine the data of Eisenhandler et al. (12) at 0.9 and 1.23 GeV/\e, shown in figures 12a and 12b; it would seem that if diffraction is responsible for the shape of the angular distribution, then a significant dip will appear at 0.9 GeV/\e when the second diffraction minimum enters the physical region. The behaviour of the dips in the elastic scattering angular distributions is shown in figure 13. At momenta above 1.8 GeV/\e, the situation is not clear, there may even be three, but at low momenta we have a clear picture of the number of dips and their t dependence. We see the second minimum crossing the physical boundary at t\approx -0.7 GeV² near 0.9 GeV/\e as mentioned above. We do not appear to have an exact measurement of where the first minimum crosses the physical boundary, but it seems plausible that some of the decrease in the backward cross-section below the 'bump' could well be from the approaching minimum.

Bizzarri et al. (17) have attempted to explain the backward direction in terms of a simple boundary condition model based on a totally absorbing sphere of radius \approx 1 fm. One of the predictions is shown on figure 11. They make the point that this model, although too simple to be the truth, suggests that diffraction may well be present. These strong suggestions that one is seeing diffractive effects makes the extraction of resonance parameters simply from the energy dependence of the backward cross-section, a dubious business.

Also shown on figure 11 is the backward charge exchange cross-section of Storer et al. (11). The cross-section is certainly of the same order of magnitude, but it doesn't seem to me to rule out the possibility that diffraction is playing a role in the low momentum region. An interesting feature is the point that both the backward charge exchange and elastic cross-section show an \approx s^{\approx 7} dependence at the higher momenta. This dependence is very similar to that in backward \K^+p elastic scattering and \bar{p}p\rightarrow k^+k^- with a k^+ in the forward direction. All these processes demand an exotic exchange.

The conclusions on the elastic channel cannot be very firm. We are perhaps seeing evidence for structure in the total cross-section. The
presence of diffraction confuses simple resonance interpretations; it
at least must be present as a significant background, and may be responsible
for most of the structure. The situation is frustrating, there is a lot
of good data but something approaching a partial wave analysis will
probably remain only a dream since we are faced with five complex amplitudes
to unravel.

V Annihilation into two pseudoscalar mesons

This channel has two amplitudes and so differential cross-section,
and asymmetry measurements could lead in principle to partial wave analyses.
The price paid for simplicity of analysis is in the cross-sections, which
are usually a few tenths of a percent of the total cross-section.

A. $\bar{p}p \rightarrow \pi^+\pi^-$

The G parity constraint on the two pions, $G = (-1)^{J+1} = 1$, provides
the I-spin of a resonance if J is known. The total cross-section is
shown in figure 14 where no obvious structure is apparent. Bubble chamber
experiments in this reaction are plagued by low statistics, so we will
concentrate on the results of three electronic experiments for information
on differential cross-sections.

1. Nicholson et al.\(^{18}\) produced 'folded' angular distributions at
12 momenta between 0.7 and 2.4 GeV/c. The data comes from two
experiments, one in which the sign of the pion is measured for
$|\cos \theta^\pi| > 0.88$, the other was a by-product of a search for $\bar{p}p \rightarrow e^+e^-$
with no sign determination, hence the folded distributions.

2. Hyams et al.\(^{19}\) measured the reaction $\pi^-p \rightarrow \pi^-p$. If one makes
the assumption, which appears to be correct, that pion exchange
dominates, then one can extract the cross-section for $\bar{p}p \rightarrow \pi^-\pi^+$
by extrapolating to the pion pole. They have data at two momenta.
18.8 GeV/c 8,461 events in the dipion mass range 1.89 to 3.2 GeV
9.8 GeV/c 13,914 events in the dipion mass range 1.89 to 2.67 GeV
One interesting feature is that they collect some data (~20%) at
mass values which correspond to antiproton momenta <700 MeV/c
in the laboratory experiments - a region where the low fluxes
make the channel very difficult to measure accurately.

3. Eisenhendler et al.\(^{20}\) used a magnetic spectrometer to collect
data at 20 momenta (-0.95$\leq\cos \theta^\pi\leq$-0.95) between 0.8 and 2.4 GeV/c.
The experiment was ~37,000 $\pi\pi$ events.

The electronic experiments, while removing the problem of poor
statistics, all have to make corrections for geometrical acceptance. The
experiment of Hyams et al. contains the physics uncertainty of assuming that one pion exchange dominates. In practice this assumption works very well. The Legendre coefficients \( A_L \) derived from an analysis of the angular distributions of the three experiments compare reasonably. There appears to be a 20\% discrepancy in normalisation between Nicholson et al. and Eisenhandler et al. but the ratios of \( A_L/A_0 \) for \( L \) even agree. The results for \( A_L/A_0 \) of Hyams et al. and Eisenhandler et al. agree moderately well with the possible exception of \( A_2/A_0 \) which shows some systematic differences\(^{(21)}\). All three groups have produced some form of analysis into resonances plus backgrounds in the partial waves.

1. Nicholson et al. have even Legendre coefficients only. They fitted with resonances plus constant backgrounds, and suggested the presence of two states.

\[
\begin{align*}
J &= 3 & M &= 2.132 \text{ GeV} & \Gamma &= 0.32 \text{ GeV} \\
J &= 5 & M &= 2.287 \text{ GeV} & \Gamma &= 0.159 \text{ GeV}
\end{align*}
\]

2. In the analysis of Hyams et al. a resonance and background term was fed into each partial wave. They find that considerable amounts of background are required and that the \( L = J-1 \) amplitudes are much greater than \( L = J + 1 \), supporting the idea of an angular momentum barrier. Their states are as follows:

\[
\begin{align*}
J &= 1 & M &= 2.27 \text{ GeV} & \Gamma &= 0.43 \\
J &= 2 & M &= 2.06 & \Gamma &= 0.2 \\
J &= 3 & M &= 2.10 & \Gamma &= 0.45 \\
J &= 4 & M &= 2.55 & \Gamma &= 0.79 \\
J &= 5 & M &= 2.59 & \Gamma &= 0.63
\end{align*}
\]

3. Eisenhandler et al.\(^{(22)}\) used a simple energy parametrisation, and resonance states were introduced with fixed mass and width after a visual examination of the Legendre coefficients. The energy dependence of the coefficients is reasonably well reproduced by the fits although the \( \chi^2 \) per degree of freedom is 5 - most of which comes from 13 points out of 220. Equally good fits can be found with no resonances. The states used are:

\[
\begin{align*}
J &= 3 & M &= 2.15 \text{ GeV} & \Gamma &= 0.27 \text{ GeV} \\
J &= 4 & M &= 2.29 \text{ GeV} & \Gamma &= 0.30 \\
J &= 5 & M &= 2.41 \text{ GeV} & \Gamma &= 0.16
\end{align*}
\]

4. In addition, Donnachie and Thomas\(^{(23)}\) have analysed the folded data of Nicholson et al. \( \pi \pi \) data from Brabson et al.\(^{(24)}\) at 3.0 and 4.0 \text{ GeV/}c and Chabaud et al.\(^{(25)}\) at 5.0 \text{ GeV/}c. They
also fit simultaneously to backward $\pi^-p$ scattering - the cross channel. They incorporate Regge baryon exchange, direct channel resonances, and a background based on the quark model of Gunion et al.\(^{(26)}\). The reason for selecting this high energy model is in order to obtain the steep $s$ dependence of the cross-sections seen at low momentum in the $\pi\pi$ channel. They suggest the following states:

\[
\begin{array}{ccc}
J &=& 3 \\
M &=& 2.13 \text{ GeV} \\
\Gamma &=& .27 \text{ GeV} \\
4 \\
M &=& 2.34 \text{ GeV} \\
\Gamma &=& .30 \text{ GeV}
\end{array}
\]

In figure 15 the positions of the above states are plotted along with the Legendre coefficients of Eisenhandler et al.\(^{(22)}\) multiplied by the square of the centre of mass momentum. There is a clustering of $3^-$ states around 2.1 GeV beneath the structure in $A_6$, but it is hard to see a consensus of opinion emerging from the analyses.

In figure 16 the states are indicated on a plot of $J$ against the mass squared. It is clear that most analyses are being guided by the intuitive ideas of an angular momentum barrier based on a radius of ~1 fm - the states lie close to, or below the curve.

In order to proceed further in these partial wave analysis polarisation data is required, otherwise there is no separation of spin flip and non spin flip amplitudes. There is one measurement of the angular distribution of the asymmetry parameter at 1.64 GeV/c by Ehrlich et al.\(^{(27)}\). The data is shown in figure 17. Donnachie and Thomas used the data as a constraint in their fit and their solution is shown. The solid curve is a solution of Eisenhandler et al.\(^{(22)}\) which contains second order backgrounds in all partial waves but no resonances. The indications are that asymmetry data will be crucial in selecting solutions since very rapid variations are predicted as a function of $\cos\theta^*$ and these change dramatically for different solutions.

In conclusion the $\pi^-\pi^+$ channel looks very promising as a possible source of resonances. The angular distributions suggest a resonance dominated system although the fits so far demand significant amounts of background. The polarisation data will be crucial and a measurement is in progress - this will be mentioned in the final section on the future outlook.

B. $\bar{p}pK^-K^+$

In this reaction we no longer have a $G$ parity constraint and the isotopic spin will have to be unravelled experimentally. The total cross-section, shown in figure 18, does not exhibit any marked structure. The angular distributions in $K^-K^+$ do not have evidence for the presence of such high partial waves as $\pi^-\pi^+$. This is quantified by the Legendre coefficients from $K^-K^+$ shown in figure 19, where the data of Eisenhandler
et al. (28) is compared - for the even coefficients - with Nicholson et al. (18).

The coefficients $A_7$ and $A_8$ are not needed, whereas $A_9$ and possibly $A_{10}$ are required in $\pi^-\pi^+$, indicating the presence of higher angular momentum states.

There has not been an attempt to perform a partial wave analysis in K$^-K^+$, although Donnachie and Thomas show that their solution is consistent with the data. Hara and Kuroda (29) using a peripheral orbit model suggest a 3$^-$ state near 2.1 GeV but the evidence is not compelling.

In this channel the final state is detected via the combinations K$^O_L$, K$^O_S$, and K$^O_S$ L which introduce some more constraints on the quantum numbers of any intermediate mesons,

- $K^O_S K^O_L$ has $C = -1 = (-1)^J$ therefore $J$ must be odd, implying $L (\bar{p}p) = J \leq 1$ - even
- $K^O_S K^O_L$ or $K^O_S K^O_L$ $C = +1$ therefore $J$ must be even; $L (\bar{p}p)$ is odd.

The most intriguing situation as far as direct channel effects exists in $K^O_S K^O_L$. Prof. Rubio reviewed the situation in detail in his contribution to this meeting. I would just like to point out briefly the discrepancy. There are two bubble chamber experiments which cover the momentum range 300 - 750 MeV/c. The cross-sections are shown in figure 20. Benvenuti et al. (30) (Wisconsin) with 71 events see structure suggesting a state at 1.97 GeV, Carson et al. (31) with 69 events see a flat cross-section. Both experiments agree from Legendre coefficients, that $L$ is even. Benvenuti et al. see an enhancement in $A2/A0$ and would like to make their state a vector meson. The situation remains unresolved.

VI Many body final states

Listed in the table below are the histories of some states which have not survived increased statistics, or have not been seen in a second experiment.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass.</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>K*(890)Kππ, K*Kππ</td>
<td>2.36</td>
<td>Seen by Oh et al. (32) in pp and pd exposure, but not confirmed when statistics improved - Oh et al. (33)</td>
</tr>
<tr>
<td>K$^O_1$K$^O_1$ π$^+$π$^-$π$^0$</td>
<td>2.37</td>
<td>Not seen by Chapman et al. (34) Proposed by Ring et al. (35) but not confirmed by the same experiment of Chapman et al. (34) when more data added.</td>
</tr>
</tbody>
</table>
$\kappa^+\kappa^-_\omega$ 2.347 A possible enhancement seen by Chapman et al.\textsuperscript{(34)}
but not present in $K^0\kappa^0_\omega$ at the predicted
level - makes resonance interpretation dubious.
Not found by Oh et al.\textsuperscript{(33)}.

$K^0_1 K^0_1\omega$ 2.176 A state proposed by Donald et al. in a
contribution to the Lund Conference but
not confirmed in the full data sample\textsuperscript{(36)}.
Not found by Oh et al.\textsuperscript{(33)}.

$\rho^0\rho^0\pi^0$ 2.19 Proposed by Kalbfleisch et al.\textsuperscript{(37)}. The
state is not supported by Bacon et al.\textsuperscript{(38)}.
The difference is not in statistics so much,
as in the mode of analysis which produces
the signal.

We are left with one slightly dubious state, the others appear to
have been caused by vagaries of low statistics.

VII Conclusions and Future Outlook

(1) We have well established total cross-section structures at
1.93, 2.19, 2.36 GeV. An isotopic spin analysis increases
the number of states to four. All states look broad except
the one at 1.93 GeV.

(2) We have not answered the question as to whether these
structures are resonances, or caused by threshold effects.
Some of the $l=1$ state at 2.36 GeV may be due to single
pion production.

(3) We appear to have bumps in the charge exchange cross-section
at 2.16 and 2.36 GeV. The experimental situation is not
entirely satisfactory but the near equality of the masses of
the states to those in the total cross-section is fairly
convincing.

(4) The elastic channel has momentum dependent effects in the
backward direction. There may be a state at 1.94 GeV, on the
otherhand it could be diffractive phenomena. We may be seeing
structure in the total elastic cross-section.

(5) The $K^0_S K^0_L$ channel has a straightforward experimental disagreement.
Is there a vector meson at 1.97 GeV?

(6) In $\rho^0\rho^0\pi^0$ the state at 2.19 GeV remains, but is contested on
analysis grounds.

The above conclusions may seem very discouraging but perhaps we can
derive some encouragement from considering $\pi N$ formation. We have argued that in $\bar{N}N$ formation we seek low spin states—two units of spin down from the leading trajectory. If we ask of $\pi N$ how many well established states have been found with two units of spin less than the leading $N\Lambda$ on $\Delta$ trajectory and a mass greater than two nucleon masses—the answer is, surprisingly few. Probably only one state makes the "three star" category, and all the candidates have come from partial wave analyses. We have possibly been too optimistic in $\bar{N}N$, expecting to identify states directly from the energy dependence of cross-sections, and may have to look to phase shift analyses.

The channel in $\bar{N}N$ formation which is most likely to achieve something approaching a phase shift analysis is $\pi\pi$. We already have several states offered from this kind of analysis. There is new data in the pipeline in this channel which should make any future states derived from it very much firmer candidates. On figure 15, three experiments are indicated.

1. The Brown-Bari-M.I.T. experiment on $\bar{p}p\rightarrow\pi^0\pi^0$—the first results were presented by Prof. Rosenson at this meeting. This data will provide an extremely useful independent constraint for the $l=0$ solutions which may emerge from the $\pi^+\pi^-$ analysis.

2. A Queen Mary College-Daresbury-Rutherford collaboration has recently finished data collection on the production of $\pi^+\pi^-$ from a polarised target. The angular distribution of the asymmetry has been measured with good statistics (~4000 $\pi\pi$ events per momentum) at 11 momenta between 1.0 and 2.2 GeV/$c$.

3. A group from Yale, responsible for the only asymmetry measurement so far, proposed to study production from polarised protons below 1 GeV/$c$.

Data from the first two experiments will be making an impact on partial wave analyses within one year, and therefore I feel that this is the most likely place from which definite statements about the formation of mesons will occur. If definite states are established one may be encouraged to extend the analysis and experiments to the $\bar{K}K$ channels.

I wish to thank the following people for communicating to me, either results, or the present status of their experiments, J. Button-Shafer, R.A. Donald, A. Donnachie, P.D. Grannis, Y. Hara, T.F. Kycia, Z. MingMa, R. Lanou, and L. Rosenson. I am grateful to the Organizing Committee for the opportunity to present this review and to the Czechoslovak Academy of Sciences and the Charles University, Prague, for the warm hospitality which we enjoyed at Liblice.
References:

(1) F. von Hippel and C. Quigg
(2) R.J. Abrams et al.
(3) A.S. Carroll et al.
(4) Z. MingMa et al.
(5) W.A. Cooper et al.
(6) Z. MingMa et al.
(7) J. Alspector et al.
(8) C. Bricman et al.
(9) D. Cutts et al.
(10) A. Colebourne et al.
(11) J. Storer et al.
(12) E. Eisenhandler et al.
(13) R. Cooper et al.
(14) D. Cline et al.
(15) M. Laloum
(16) J.K. Yoh et al.
(17) R. Bizzarri et al.
(18) H. Nicholson et al.
(19) B. Hyams et al.
(20) E. Eisenhandler et al.
(21) E. Eisenhandler et al.
(22) E. Eisenhandler et al.
(23) A. Donnachie and P.R. Thomas
(24) A. Brabson et al.
(25) V. Chabaud et al.
(26) J.F. Gunion, S.J. Brodsky and R. Blankenbecler
(27) R.D. Ehrlich et al.
(28) E. Eisenhandler et al.
(29) Y. Hara and T. Kuroda
(30) A. Benvenuti et al.
(31) R.G. Carson et al.
(32) B.Y. Oh et al.
(33) B.Y. Oh et al.
(34) J.W. Chapman et al.
(35) H. Ring et al.
(36) R.A. Donald et al.
(37) G. Kalbfleisch et al.
(38) T.C. Bacon et al.

ANL/HEP 7129 (1971)
Nucl. Phys. B51 (1973) 77
Phys. Rev. Lett 30 (1973) 511
Stony Brook, Wisc., preprint, to be published
Contribution to London Conference July 1974
Liverpool, Glasgow, preprint to be published June'74
Phys. Rev. Lett. 21 (1968) 1268
CERN 72-10 (Chevres Symposium on Nucleon Antinucleon Interactions 1972)
Phys. Rev. D6 (1972) 160
Phys. Rev. D7 (1973) 2572
CERN-Munich preprint, to be published in
Nucl. Phys. B
Phys. Lett. 47B (1973) 531
QMC/Liverpool/DL/RL, to be published in
Nucl. Phys. B
Phys. Lett. 47H (1973) 536
Nuovo Cim. Lett. 7 (1973) 285
Phys. Lett. 42B (1972) 287
Phys. Lett. 41B (1972) 239
Phys. Rev. D8 (1973) 287
Phys. Rev. Lett. 28 (1972) 1147
Contribution to London Conference July 1974
CERN Theory preprint CERN TH 1877
Phys. Rev. Lett. 27 (1971) 283
Contribution to NAL Conference, NAL, Sept. 1972
(University of Massachusetts and Tokyo)
Nucl. Phys. B51 (1973) 57
University of Michigan report 1969 (unpublished)
Phys. Lett. 408 (1972) 586
Phys. Lett. 29B (1969) 259
Phys. Rev. D7 (1973) 577
Table 1
Angular momentum barrier factor $B_\lambda$ for the coupling of a state to $\pi\pi$, $kk$, and $\bar{p}p$. The figures in brackets have an additional relative phase space factor included.

<table>
<thead>
<tr>
<th>$J$</th>
<th>$B_\lambda$</th>
<th>$\pi\pi$</th>
<th>$kk$</th>
<th>$\bar{p}p$ (l = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.45</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.75 (l = 2)</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.72</td>
<td>0.39</td>
<td></td>
</tr>
</tbody>
</table>

Table 2
The states derived from the total cross-section measurements.

<table>
<thead>
<tr>
<th>MASS</th>
<th>I</th>
<th>D</th>
<th>l</th>
<th>$\langle j,\phi \rangle$</th>
<th>$\langle j+\frac{1}{2},x \rangle$</th>
<th>x</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1932^{+2}_{-3}</td>
<td>9^{+4}_{-3}</td>
<td>.475</td>
<td>1 (7)</td>
<td>18</td>
<td>.19</td>
<td>.15</td>
<td>2</td>
</tr>
<tr>
<td>2190^{+14}_{-10}</td>
<td>85</td>
<td>1.32</td>
<td>1</td>
<td>5.5</td>
<td>.36</td>
<td>.21</td>
<td>3</td>
</tr>
<tr>
<td>2350^{+10}_{-10}</td>
<td>140</td>
<td>1.77</td>
<td>1</td>
<td>3.2</td>
<td>.32</td>
<td>.14</td>
<td>4</td>
</tr>
<tr>
<td>2375^{+10}_{-10}</td>
<td>190</td>
<td>1.84</td>
<td>0</td>
<td>2.5</td>
<td>.27</td>
<td>.12</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3
A comparison of RAS with the total cross-section data.

<table>
<thead>
<tr>
<th></th>
<th>M</th>
<th>$\Gamma$</th>
<th>h(mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R A S</td>
<td>2192.7^{+1.2}_{-1.5}</td>
<td>97.6^{+8.1}_{-5.9}</td>
<td>2.32^{+0.13}_{-0.08}</td>
</tr>
<tr>
<td>Abrams et al.</td>
<td>2187^{+3}_{-3}</td>
<td>56^{+8}_{-8}</td>
<td>1.85^{+2.5}_{-2.5}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>M</th>
<th>$\Gamma$</th>
<th>h(mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R A S</td>
<td>2359^{+1.4}_{-1.2}</td>
<td>164.9^{+17.9}_{-7.6}</td>
<td>2.06^{+0.12}_{-0.12}</td>
</tr>
<tr>
<td>Abrams et al.</td>
<td>2363^{+2}_{-2}</td>
<td>171^{+1.0}_{-1.0}</td>
<td>2.52^{+2.28}_{-2.28}</td>
</tr>
</tbody>
</table>

Table 4
Predicted enhancements to the total elastic cross-section with $J$ value assumed and hence $x$ is determined from the total cross-section states.

<table>
<thead>
<tr>
<th>D</th>
<th>J</th>
<th>mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>.475</td>
<td>2</td>
<td>2.6</td>
</tr>
<tr>
<td>1.32</td>
<td>3</td>
<td>1.2</td>
</tr>
<tr>
<td>1.77</td>
<td>4</td>
<td>.430</td>
</tr>
<tr>
<td>1.84</td>
<td>4</td>
<td>.300</td>
</tr>
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</table>
Figure Captions

1. A comparison of angular momentum barrier effects in π−N and N̅N formation based on a simple impact parameter radius of 1 fm.
2. \( \bar{p}p \) total cross-section from .385 to 2.5 GeV/\( c \), data from Abrams et al. and Carroll et al.
3. The low momentum \( \bar{p}p \) and \( \bar{p}d \) total cross-section of Carroll et al.
4. Single pion production cross-sections in \( l = 1 \) and \( l = 0 \) states data from Z. MingMa et al.
5. The results from R.A.S. for \( \sigma_T(\bar{p}p) \)
6. The total cross-section for \( \bar{p}p \rightarrow N\bar{N} \). Data from experiments which have no reference given can be found in "\( N\bar{N} \) and \( \bar{N}D \) Interactions - a Compilation" LBL-58 May 1972.
7. The data from Cutts et al. plotted as \( \sigma(\bar{p}p \rightarrow \bar{N}\bar{N}) \times P_{lab} \).
8. Data on the total elastic cross-section.
9. A preliminary result on the total elastic cross-section from the data of Eisenhandler et al. (12).
10. The total elastic cross-section of Cooper et al. - Liverpool-Glasgow collaboration.
11. The backward elastic cross-section showing data from College de France, Cline et al., Yoh et al., Eisenhandler et al., and the theoretical curve of Bizzarri et al., also plotted is the backward charge exchange data of Storer et al.
12. Angular distributions for \( \bar{p}p \) elastic scattering from Eisenhandler et al. a) 0.9 GeV/\( c \) b) 1.23 GeV/\( c \).
13. The t value of the dips in \( \bar{p}p \) elastic scattering plotted as a function of lab momentum.
14. The total cross-section for \( \bar{p}p \rightarrow \pi^−\pi^+ \).
15. The Legendre Coefficients of Eisenhandler et al. for \( \bar{p}p \rightarrow \pi^−\pi^+ \). The coefficients are multiplied by centre of mass momentum squared.
16. The states derived from the analyses of \( \bar{p}p \rightarrow \pi^−\pi^+ \) on a plot of J versus mass squared.
17. The asymmetry data of Ehrlich et al. for \( \bar{p}p \rightarrow \pi^−\pi^+ \).
18. The total cross-section for \( \bar{p}p \rightarrow K^-K^+ \).
19. The Legendre Coefficients for \( \bar{p}p \rightarrow K^-K^+ \) of Eisenhandler et al., and the even coefficients of Nicholson et al.
20. The total cross-section for \( \bar{p}p \rightarrow K_S^0 K_L^0 \). data from Carson et al. and Benvenuti et al.
Fig. 1

Fig. 2
Fig. 5

Fig. 6
Fig. 11
Fig. 12
Fig. 13

Fig. 14
Fig. 16

$M^2 \ (GeV/c^2)^2$

Fig. 17

$A (\cos \theta^*)$

$\cos \theta^*$
Fig. 18

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure18}
\end{figure}

- Bizzarri et al.
- Bacon et al.
- Mandelkern et al.
- Chapman et al.
- Fields et al.
- Nicholson et al.
- Eisenhandler et al. (28)
Fig. 19
Fig. 20

TOTAL CROSS SECTION
\( \bar{p}p \rightarrow K^0 L^0 \)

Carson et al. (31)

TOTAL CROSS SECTION
\( \bar{p}p \rightarrow K^0 L^0 \)

Benvenuti et al. (30)
- Smith:
  In the CERN-Munich experiment, producing $p\bar{p}$ in $\pi N$ collisions, can one really say that one-pion exchange dominates?

- Šimák:
  Do you have graphs about the angular correlations, in particular the Yang-Treiman angular distributions in the CERN-Munich experiments?

- Astbury:
  They were good. It seems that they are as good as in $\pi N \rightarrow \pi \pi N$. It looks like pion exchange.

- Lillestøl:
  If the pion exchange is present, it still does not mean that it dominates; one should make an extrapolation down to the pole.