INTRODUCTION

Bubble chambers have played an immensely important role in developing our understanding of meson resonances. As a matter of fact, if we look at the four lowest lying meson nonets: $0^+$, $1^-$, $2^{++}$, and $1^{++}$, all the 27 states in the last three nonets were discovered via the bubble chamber technique. In addition, their spins and parities were also determined in bubble chamber experiments. Bubble chambers were also important in obtaining information about the members of the first nonet which contains states stable against decays via strong interactions. Both $\eta$ and $\eta'$ were discovered and identified as $0^+$ states in bubble chamber experiments; the same technique also provided spin and/or parity information about $K$ mesons and $\pi^0$.

It is natural to ask why bubble chambers were such a dominant technique in this area of particle physics. I believe that there was a fortunate confluence of several factors which contributed to this success. I will enumerate them briefly:

a) Large hydrogen bubble chambers were constructed successfully and thus offered pure proton targets, $4\pi$ solid angle coverage for interaction products, and measurement precision that was quite good for that era.

b) Relatively pure separated beams became available which satisfied the need for providing $\bar{p}$'s and $K$'s without simultaneous presence of much more numerous $\pi$'s.

c) "Semi-automatic" scanning and measuring equipment was developed which allowed conversion of large amounts of data from film image to digital form.

d) High speed computing, just becoming available, allowed creation of powerful programs to do geometrical reconstruction of tracks, kinematical fitting of whole events, and summaries of computed quantities from a number of events. I would like to acknowledge here two important pioneers in this area who passed away prematurely - Frank Solmitz from Berkeley and Howard Taft from Yale.

e) Interesting physics was well matched to bubble chamber technology. More specifically, to achieve many physics goals it was important to be able to identify and measure tracks with lengths ranging from 1 mm to 10 cm and to do multi-particle correlations. Bubble chambers were very well suited to achieving those goals.
Finally, one should not underestimate the vision of few individuals who had the foresight to anticipate the power of the bubble chamber technique and take steps to make it a reality. Certainly one of the foremost among these was my own mentor, Luis W. Alvarez.

The bubble chamber results dominated the field of meson resonances for the first half of the decade of 1960's. By the end of that decade they were pretty much superseded by other techniques. This historical review will focus on these five golden years of bubble chambers. Space requires me to be selective so only the most important highlights will be described.

I will start with a brief account of the overall situation in particle physics at the end of the 1950's. Then I will discuss the most important experimental results on some of the lower lying meson resonances. Finally, I will conclude with some personal opinions as to the reasons for the fade-out of bubble chamber techniques.

1. SITUATION IN THE LATE 1950's

I will focus here on three general aspects: theoretical ideas, results available and experimental capabilities. The explosion in the area of meson (as well as baryon) resonances was certainly not anticipated. The theoretical efforts to understand the "elementary" particle spectrum were still in infancy at the end of 1950's. Symmetry ideas to understand the particle spectrum were just beginning to be fashionable. The so-called "global symmetry" attempted to relate the strange baryons to the nucleon doublet [1]; there was some speculation that one might find an analogue to the famous $\pi^-\text{N}$ resonance below $\pi^-\text{N}$ threshold, predicted by Dalitz and Tuan [3] based on analysis of $Kp$ data at rest and at low energies, was a good example in the baryon sector. In the meson sector, there were many attempts to understand the dynamics of the meson-meson system, mainly focusing on the $\pi^-\pi^+$ system where an effort was being made to relate the behavior of that system to nucleon electromagnetic form factors. There was a prediction by Frazer and Fulco [4] that a $\pi\pi$ resonance will be found around 500 MeV.

An important parallel effort, that had strong impact on experimental work, was development of formalism to study scattering on unstable targets, in analogy with the impulse approximation relevant to collisions in which the deuteron is broken up. Probably the most famous of these was the one pion exchange (OPE) model developed by Chew and Low [5], which gave a prescription as to how one could extract the $\pi\pi$ cross section from peripheral pion production by pions. Determination of this cross section, which involved extrapolation to unphysical region and thus required large statistics, would in principle allow one to see $\pi^+\pi^-$ resonances. Much less theoretical work was done on the $\pi-K$ system, but there too some tentative predictions were made of existence of resonant states, both in the $S$ wave [6] and in the $P$ wave [7].

There were very few experimental results in the area of $n$-body resonances. Of course, the $3,3$ resonance in the $\pi$-nucleon system was discovered some time before that and its parameters were well understood by the time 1960 arrived [8]. But the $\pi$-nucleon system at energies above this resonance was still relatively unexplored. In the multi-meson system sector there were even fewer data. There was an anomalous result, dubbed the ABC effect [9] after the initials of its three authors, which indicated an excess of events above phase space in the region of low effective mass of $\pi^+\pi^-$ pairs, resulting from $pd$ collisions producing one or more $\pi$'s together with $\text{He}^3$ or $\text{H}^3$. This experiment looked only at the recoil nucleus and could not provide information on the details of the di-pion system.

The paucity of data relevant to possible existence of resonant states among strongly interacting particles could be understood as due to lack of adequate instrumentation available at that time to perform such studies. The era of $4\pi$ electronic detectors was still more than a decade away. Drift
chambers, proportional wire chambers or even wire spark chambers were still some time from being invented. Pure counter experiments were still mainly 1-arm spectrometer experiments. 2-arm experiments, to study elastic scattering were just being initiated. Emulsions could not handle the rates of events necessary for these studies and were ill suited to look for neutral unstable particles with typical path lengths of several cm. The cloud chambers did not provide sufficient mass for interactions. Clearly, the physics was waiting for the invention and development of bubble chambers.

2. EXPERIMENTAL RESULTS

2.1. $K^*$ (892)

This was the first meson resonance discovered. Its first observation was made by the Berkeley group [10] in the reaction

$$K^+ p \rightarrow K^0 \pi^- p$$

produced in the 15" hydrogen bubble chamber exposed to a separated 1.15 GeV/c $K^+$ beam. The Dalitz plot for the 48 examples of this reaction is shown in Figure 1. A pronounced clumping is seen in a region corresponding to a unique value of $T_p$, which, because of almost monochromatic nature of the beam, is equivalent to a unique value of $M^2(K^0\pi^-)$. The mass spectrum of the $K^0\pi^-$ system is shown in Figure 2. The original mass and width parameters (885 MeV and 16 MeV) were lower than the currently accepted ones, presumably due to close proximity of the mass peak to the kinematical limit. The decay angular distribution of the $K^*$ was consistent with isotropy and allowed one to exclude spin values greater than or equal to 2, on the assumption that the $K^*$ system was produced predominantly in the S state. Subsequent analysis [11] of the channel

$$K^- p \rightarrow K^- \pi^0 p$$

indicated presence of a similar peak in the $K^-\pi^0$ system. The ratio of events in the peak for the two channels was consistent with

$$N(K^0\pi^-)/N(K^-\pi^0) = 2$$
as expected from the $T = 1/2$ assignment and excluded the $T = 3/2$ possibility. Thus the key remaining question was whether the spin parity assignment was $0^+$ or $1^-$ and the subsequent experiments focused on that issue.

![Figure 1](image1.png)

Figure 1. Phase-space plot of the 48 examples of $K^+ p \rightarrow K^0 + \pi^- + p$ reactions. The diagonal line represents central value of the $\Delta$ (1232) resonance (from Ref. 10).

![Figure 2](image2.png)

Figure 2. Mass spectrum of the $K^0 - \pi^-$ system. The solid line represents the phase-space curve normalized to background events (from Ref. 10).
A much larger sample of events, obtained from interactions of 1.22 GeV/c $K^-$ in the 72° bubble chamber to give $\bar{K}^0\pi^0\rho$ final state was analyzed for anisotropy in all possible angles characterizing the $K^*$ decays [12]. Such an anisotropy would be clear evidence of spin 1. No statistically significant effect was seen and thus no definite conclusion could be drawn.

At the same time the CERN - College de France-Ecole Polytechnique collaboration [13] obtained strong evidence for $J = 1$ assignment based on their data from $\bar{p}p$ annihilations in an 80 cm HBC exposed to a stopping $\bar{p}$ beam at the CERN proton synchrotron. They used the argument put forth by M. Schwartz [14] several months earlier who showed that in the reactions

$$\bar{p}p \rightarrow K^0 + K^{*0} \text{ or } \rightarrow \bar{K}^0 + K^{*0}$$

if the $\bar{p}p$ capture occurs from an S state and if $J_{K^*} = 0$, then one would not observe in these reactions final states with both a $K^0_S$ and a $K^0_L$, but would see only two $K^0_S$'s or two $K^0_L$'s. This restriction does not hold if $J_{K^*} = 1$. This conclusion comes from invariance of the strong processes under charge conjugation.

Figure 3 shows the momentum spectrum of the produced $K^0_S$ for the events where no other $K^0_S$ is present. Two peaks are clearly seen, the higher one corresponding to a recoiling $K^0$ and the lower one (at about 600 MeV) to a recoiling $K^*$. Since no second $K^0_S$ was seen, the recoiling $K^*$ had to decay either via $K^0_L\pi^0$ or via $K^0_L\pi^0$ with $K^0_L \rightarrow 2\pi^0$. The contribution of the second process could be estimated by looking at events with $2K^0_S$ (Figure 4) with both $K^0_S$'s decaying via $\pi^+\pi^-$ mode. There is a possible small excess of events at 600 MeV but certainly not enough to explain the peak in Figure 3. Putting in all the appropriate corrections and values of relevant branching ratios, the authors estimated that there were $36.5 \pm 15$ events with $K^0_S$ and $K^0_L$ resulting from the intermediate $K^0 + \bar{K}^0$ or $K^{*0} + \bar{K}^0$ channel. To the extent that this number is inconsistent with zero, one can conclude that $J_{K^*} = 1$. 

![Figure 3](image1.png)

Figure 3. Momentum spectrum of the $K^0_S$ from the reaction $\bar{p} + p \rightarrow K^0_S + \text{neutral particles}$. Dashed histogram represents observed events; the solid one is corrected for decay probabilities (from Ref. 13).

![Figure 4](image2.png)

Figure 4. Momentum spectrum of the $K^0_S$ from the reaction $\bar{p} + p \rightarrow K^0_S + K^0_S + \text{neutral particles}$. Dashed histogram represents observed events; the solid one is corrected for decay probabilities (from Ref. 13).
A very elegant and first conclusive evidence for \( J_{K^*} = 1 \) was provided shortly afterwards [15] by a Berkeley group who studied the events

\[ K^* p \rightarrow K^* p \pi^+ \pi^- \]

at \( P_{K^*} = 2.0 \text{ GeV}/c \). It was found that most of these events proceeded via intermediate \( K^* (892) + \Delta (1232) \) state, with subsequent \( K^* \) and \( \Delta \) decays into \( K^+ \pi^- \) and \( p \pi^+ \) respectively. Furthermore, production process appeared to be very peripheral suggesting one pion exchange (OPE) mechanism. This would require specific alignment of both the \( K^* \) and the \( \Delta \) and a \( \cos^2 \alpha \) decay distribution for the \( K^* \), \( \alpha \) being the Adair angle. This was indeed observed as can be seen in Figure 5.

For completeness, I would like to mention two other experiments which subsequently provided additional evidence that \( J_{K^*} = 1 \). The \( K^* \)'s produced in the reaction [16]

\[ \pi^- p \rightarrow \Sigma^- K^0, K^0 \rightarrow K^* \pi^- \]

appeared to be aligned but in a way that suggested strong contribution from the \( K^* \) exchange as demonstrated by the angular distributions shown in Figure 6. The non-isotropy by itself is evidence of \( J_{K^*} \neq 0 \), and consistency with predictions of the exchange model strongly supports \( J_{K^*} = 1 \) assignment.

Finally, exploration of the reaction [17]

\[ K^- p \rightarrow K^- \pi^- p \]

at higher energies, \( 1.55 < P_{K^*} < 1.75 \text{ GeV}/c \), and with very good statistics, allowed one to obtain sufficient sample of events close to \( 0^0 \) production angle where OPE diagram should be dominant. Analysis of the \( \pi K \) scattering angle in that model (Figure 7) as a function of \( M(K\pi) \) shows clear dominance of the \( J = 1 \) resonance near \( M(K\pi) = M_{K^*} \) and characteristic S-P interference just below and just above the resonant region.

### 2.2. \( \rho \) Resonance

In contrast to the \( K\pi \) system, the \( \pi\pi \) system was subject of extensive theoretical studies towards the end of the 50's and there were a number of predictions about existence of a \( \pi-\pi \) resonance [4]. At least initially, the experimental work was strongly influenced by ideas of Chew and Low [5] who described a procedure by which \( \pi\pi \) cross section could be obtained by extrapolating the physical angular distribution to the pion pole.

The subject of \( \pi\pi \) resonances also became a topic of competition between the bubble chamber and counter techniques. In my opinion this competition demonstrated that the counter technique was still in relative infancy as far as the study of multi-particle systems were concerned and even relatively Herculean efforts had a hard time making it competitive with bubble chambers.
Figure 6. (a) \(K^*\) decay relative to the normal, \(n\), to the \(\Sigma^0 K^*\) production plane. (b) \(K^*\) decay relative to \(\vec{l}\), the direction of the incident pion in the \(K^*\) rest frame. (c) \(K^*\) decay relative to \(\vec{l} \times \vec{n}\). (d) Azimuthal distribution of the \(K^*\) decay measured in the plane defined by \(n\) and \(\vec{l} \times \vec{n}\). Here \(\phi = 0\) is selected along \(\vec{n}\). The curves are predictions of the exchange model with contributions from both \(K\) and \(K^*\) exchange (from Ref. 16).

Figure 7. Distribution in the \(K\pi\) scattering angle for events with incident \(K\) momenta between 1.55 and 1.75 BeV/c. (a) \(M(K\pi) < 800\) MeV, (b) \(800 < M(K\pi) < 865\) MeV, (c) \(865 < M(K\pi) < 910\) MeV, (d) \(910 < M(K\pi) < 960\) MeV, and (e) \(M(K\pi) > 960\) MeV (from Ref. 17).
The Berkeley group [18] studied $\pi^+ p$ interactions at 1.03 GeV/c in the 72" bubble chamber and looked for the process

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

where the reaction was relatively peripheral, i.e., the final state proton was slow. It is this kinematical region that is most influenced by the pion pole and therefore these data play the largest role in the extrapolation. The results of the extrapolation yield a $\pi\pi$ scattering cross-section (Figure 8) which indicates presence of a $J = 1$ resonance in the vicinity of 700 MeV. However, as the authors pointed out, the extrapolation becomes less accurate as one goes to the higher mass regions.

The first evidence for the $p$ in the physical region was obtained by the Wisconsin group [19] by studying $n-p$ interactions at 1.9 GeV at the Brookhaven Cosmotron in the 14" HBC and by the Yale/BNL group [20] from $n\pi^+$ interactions in the BNL 20" bubble chamber. The Wisconsin data for low momentum transfer events are shown in Figure 9. The data were consistent with the Berkeley results and demonstrated that the size of the peak for the low $q^2$ events, when interpreted in the framework of the Chew-Low formalism, gave a value consistent with the presence of a $J = 1$ resonance around 750 MeV.

The Yale group $\pi\pi$ mass histograms are shown in Figure 10. The $\pi\pi^0$ data exhibit a slight shift in the peak as a function of incident energy due to the phase space effect. There is no evidence at all for a peak in the $\pi^+\pi^+$ spectrum providing strong supporting evidence for the $T = 1$ isotopic spin assignment, and thus, through Bose statistics argument, for a $J = 1$ value.

More direct evidence for spin 1 assignment of the $p$ was provided by the Berkeley group [21] who studied $\pi^- p$ differential cross section below, at, and above the resonance resulting from the reaction

$$\pi^- p \rightarrow \pi^- p$$

at 1.25 GeV/c in the 72" HBC. Their results are displayed in Figure 11 and show not only the strong $\cos^2 \theta$ term, characteristic of a $J = 1$ state at the resonance, but also the S-P interference effects below and above it.

To conclude the discussion on the $p$ meson, I would like to give a brief description of the competing counter experiment [22] and the results derived from it. The experiment involved a $\pi^+$ or $\pi^-$ beam incident on a hydrogen target that was surrounded by a number of pion detecting counters. Six of these were polar angle measuring counters and twelve others measured the azimuthal angle. In addition, downstream of the target there was a large dish composed of 84 neutron counters arranged in 12 azimuthal sectors, each with seven polar angle measuring counters.
Figure 10. Distribution of pion-pion $Q$ values (kinetic energy of the two outgoing pions in their mutual center-of-momentum system) for the reactions $\pi^+ + p \rightarrow p + \pi^+ + \pi^0$ (a-c) and $\pi^- + p \rightarrow n + \pi^+ + \pi^-$ (d-f) at 910-MeV, 1090-MeV, and 1260-MeV laboratory kinetic energy of the incident pion. The curved lines are the $Q$ distribution resulting from uniform distribution of the secondary particles in momentum space (from Ref. 20).
Figure 11. Histograms showing the differential $\pi\pi$ cross sections below the resonance (a), at the resonance (b), and above the resonance (c). The smooth curves are least-squares fits to the data (from Ref. 21).

The dish covered polar angle from $4^\circ$ to $60^\circ$. The apparatus is illustrated in Figure 12. All the counter information was correlated with the time of flight information and kinematic fit was made to a three body $\pi\pi\pi$ final state. The results of the experiment, expressed as $\pi\pi$ cross section are illustrated in Figure 13. Clearly a peak at the mass of the $\rho$ is seen in the $\pi^+\pi^-$ system; no evidence of a peak is seen in the $\pi^+\pi^-\pi^0$ final state, as expected from the quantum number assignments of the $\rho$.

2.3. $\omega$ Resonance

The existence of a heavy $T = 0$, $J^P = 1^-$ meson was predicted as early as 1957 by Nambu [23], the motivation being to explain the electromagnetic form factors of the proton and the neutron. Subsequently, Chew [24] argued that such a particle should exist on dynamical grounds as a resonance in the three pion system. J.J. Sakurai [25] postulated two $T = 0$ vector mesons, one coupled to the baryonic current and the other to the hypercharge current. Finally, if SU(3) is to be a valid symmetry of strong interactions, one needs such a particle as a partner to the previously discussed $\rho$ and $K^*$ (892).

The first evidence for such a particle, called $\omega$, came from a Berkeley group [26] which studied the reaction

$$\bar{p}p \rightarrow \pi^+\pi^+\pi^-\pi^-\pi^0$$

produced in the 72° HBC exposed to a beam of 1.61 GeV/c antiprotons. Whereas the doubly charged 3-pion combinations (2 per event) and singly charged combinations (4 per event) show an effective mass spectrum consistent with phase space, the neutral 3-pion combinations show a pronounced peak at a mass of 787 MeV (Figure 14) which could be associated with the previously postulated $T = 0$, $J^P = 1^-$ meson.

Shortly afterwards, study of another channel [27] from the same experiment

$$\bar{p}p \rightarrow \pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$$

showed very similar results indicating that this reaction was also dominated by the $\omega$ production and subsequent decay into 3 pions.
To associate the observed 787 MeV resonance with the postulated \( J^P = 1^- \) particle, one had to verify its spin and parity assignment.

Since a \( 0^+ \) particle cannot decay into three pseudoscalar mesons, the lowest possible spin parity assignments were \( 0^- \), \( 1^- \), and \( 1^+ \). Proper identification can be made by plotting the events in the peak on a Dalitz plot, in a manner analogous to that used by Dalitz [28] several years earlier in trying to determine spin parity of the \( K \) meson responsible for \( K^+ \rightarrow \pi^+ \pi^0 \pi^- \) decay. Since the matrix element describing the decay process has to have transformation properties consistent with the \( J^P \) assignment of the parent particle, the Dalitz plot population density will be different for the above three \( J^P \) assignments. More specifically, the population density will vanish in different places on the plot depending on the \( J^P \) assignment.
The form and properties of the three relevant matrix elements are summarized in Table I. They represent special cases of a more general treatment given somewhat later by Zemach [29]. The first detailed analysis of this nature was performed by Stevenson et al [30] on the events from the $5\pi$ sample (Figure 15) who showed that the data strongly supported the $J^P = 1^-$ assignment. Similar conclusion was obtained from the analysis of the $7\pi$ event sample [27].

Table I:

Possible three-pion resonances with $T = 0$, $J \leq 1$

<table>
<thead>
<tr>
<th>Meson</th>
<th>Type</th>
<th>$J$</th>
<th>$l$</th>
<th>$L$</th>
<th>Simple example</th>
<th>Matrix element</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V$</td>
<td>$1^-$</td>
<td>1</td>
<td>1</td>
<td>$(p_0 x p_+)+ (p_+ x p_0) + (p x p_0)$</td>
<td>Whole boundary</td>
</tr>
<tr>
<td></td>
<td>$PS$</td>
<td>$0^-$</td>
<td>1 and 3</td>
<td>1 and 3</td>
<td>$(E_+ - E_0) (E_0 - E_+)(E_+ - E_0)$</td>
<td>Straight lines</td>
</tr>
<tr>
<td></td>
<td>$A$</td>
<td>$1^+$</td>
<td>0 and 2</td>
<td>1</td>
<td>$E_+ (p_0 Site x p_0) + E_0 (p_+ x p_0) + E_+ (p_- x p_0)$</td>
<td>Center, b, d, f</td>
</tr>
</tbody>
</table>

Figure 13. $\sigma_{\pi\pi}$ obtained by integration over $p^2$ in the physical region (from Ref. 22).

Figure 14. Number of pion triplets versus effective mass ($M_{3\pi}$) of the triplets for reaction $\bar{p} + p \rightarrow 2\pi^+ + 2\pi^- + \pi^0$; (a) distributions for $|Q| = 1$ and $|Q| = 2$ triplets, (b) distribution for $Q = 0$ triplets (from Ref. 26).
Figure 15. Dalitz plot, folded six times, of the 241 \( \pi^+ \pi^- \pi^0 \) triplets in the control region (a) and of the 270 triplets in the \( \omega \) peak region (b). The coordinates are the normalized Dalitz variables \( x = (T_+ - T_-) / \sqrt{3Q} \) and \( y = T_0 / Q \) \((Q = T_+ + T_- + T_0 = M_3 - 3)\). Projections on the Dalitz plot for sectors A1 through A5 (c) and for sectors B1 through B5 (d) for the peak region. The smooth curves are the probability distributions for the three competing matrix elements (from Ref. 30).
The data discussed so far were consistent with negligible width but because of relatively large experimental resolution, ±12 MeV on each pion triplet, an accurate determination of the width was not possible. That measurement was performed by the Columbia-Rutgers group [31], utilizing \( \bar{p}p \) annihilations at rest to give

\[ \bar{p}p \rightarrow K^+ K^- \omega, \quad \omega \rightarrow \pi^+ \pi^- \pi^0. \]

The overall kinetic energy available for the three initial final state particles is quite small and thus the 2 \( K^- \)'s frequently came to rest in the bubble chamber. In these cases their momenta and energies can be determined very accurately from range and thus the mass of the \( \omega \) can be measured with the precision of 1-2 MeV. The observed events have been plotted in Figure 16 as an ideogram to allow for variation in mass reconstruction errors from event to event. The experimental width is clearly broader than the resolution function and allows one to quote a value \( \Gamma^{\omega} = 9.5 \pm 2.1 \text{MeV} \).

Figure 16. Ideogram of the \( \bar{p}p \rightarrow K^+ K^- \pi^+ \pi^- \pi^0 \) events in the \( \omega \) region with resolution function and best-fit resonance curve (from Ref. 31).

Figure 17. Histogram of the effective mass of the three-pion system for 233 events (from Ref. 32).

2.4. \( \eta \) Meson

Shortly after the discovery of the \( \omega \) meson, evidence was presented by the Johns Hopkins-Northwestern group [32] for another resonance in the \( \pi^+ \pi^- \pi^0 \) system, this one at a mass of 550 MeV. In a study of \( \pi^+ d \) interactions at 1.85 GeV in the 72'' bubble chamber, the \( 3\pi \) mass spectrum from the process

\[ \pi^+ d \rightarrow pp\pi^+ \pi^- \pi^0 \]

was shown to exhibit two clear peaks (Figure 17), the higher lying one corresponding to the \( \omega \) and the lower one indicating a possible new state.
There were two theoretical ideas which might possibly be vindicated by this observation. One possibility was that the new state was the second vector meson predicted some time ago by J.J. Sakurai [33] within the framework of his vector theory of strong interactions. Such a state, which he named $\eta$, would be coupled to the hypercharge current, and would require a $J^P = 1^-$ assignment.

The other possibility was that the new state was the last member of the pseudoscalar SU(3) octet that contained $K$ and $\pi$ mesons. This assignment would require $J^P = 0^-$. The G parity of this state would have to be even and thus decay to a $3\pi$ final state via strong interactions would be forbidden. The observed decay, in this assignment, would have to proceed with emission and reabsorption of a virtual photon.

There were a number of ways that one could distinguish between these possibilities. Historically the most important ones were: ratio of all neutral to charged decay modes, population of Dalitz plot, and absence or presence of the $2\gamma$ decay mode. I shall discuss each one of these briefly.

For a $J^P = 0^{++}$ assignment, an important all neutral channel could be $2\gamma$; the other all neutral channel would be $3\pi^0$. For a $1^-$ assignment, the only important all neutral channel would be $\pi^0\gamma$, but it would be expected to be down by one power of $\alpha$. ($3\pi^0$ final state is forbidden by the required complete spatial antisymmetry of the $T = 0$ three-pion state for this $J, P, G$ assignment.) Since the $3\pi$ decay mode is suppressed for $0^-$ choice, the $2\gamma$ mode could be quite important and thus neutral to charged ratio could be high.

First information on this question was provided by Bastien et al. [34] from a study of the reaction

$$K^-p \rightarrow \Lambda \eta$$

at 760 MeV/c, i.e., just above the threshold. Plot of the missing mass for events where only the $\Lambda$ was visible in the final state showed a clear peak at 550 MeV/c as shown in Figure 18a. A similar peak was seen for the $\pi^+\pi^-\pi^0$ spectrum (Figure 18b). The ratio of these two peaks, after correcting for detection efficiencies, gave $B$ (charged)/$B$ (neutral) = 0.33 $\pm$ 0.11. This would make the $0^+$ assignment appear much more likely than the $1^-$ one.

Of course, theoretical prejudices aside, one should also consider other possibilities, i.e., $0^+$, $1^+$, $1^{++}$, and $1^++$. The Dalitz plot analysis would in principle be able to distinguish among all six of these $J^P$ possibilities. In the previous discussion of the $\omega$ Dalitz plot we have already described the population density for a $3\pi$ Dalitz plot for the $G = -1$ states. In Table II we present the relevant parameters for the $G = +1$ states. All of these have to proceed via electromagnetic interactions since the $3\pi$ final state has $G = 1$ parity.

We also recall that $G = C(-1)^T$ and that for $T = 1$ the maximum ratio of $3\pi^0/\pi^+\pi^-\pi^0$ is 1.5. The latter isotopic spin assignment, however, is unlikely [35] from upper limits obtained on possible production of charged states of the $\eta$. 

![Figure 18. Mass spectrum of the system recoiling against $\Lambda$.](image)
Table II:
The G-forbidden $3\pi$ decays$^a$

<table>
<thead>
<tr>
<th>Meson</th>
<th>$I, L$</th>
<th>Simplest matrix element</th>
<th>Vanishes at</th>
<th>Dominant radiative decay modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+$</td>
<td>0,0</td>
<td>$\alpha$</td>
<td>nowhere</td>
<td>$2\gamma, \pi^+\pi^-\gamma$</td>
</tr>
<tr>
<td>$1^{++}$</td>
<td>1,0</td>
<td>$\alpha \hat{p}$</td>
<td>$T_{\pi^0} = 0$</td>
<td>$\pi^+\pi^-\gamma$</td>
</tr>
<tr>
<td>$1^+$</td>
<td>2,2</td>
<td>$\alpha (\hat{p} \times \hat{q}) (\hat{p} \cdot \hat{q})$</td>
<td>$T_{\pi^0}$ axis and boundary</td>
<td>$\pi^+\pi^-\gamma$</td>
</tr>
</tbody>
</table>

$^a$ The factor $\alpha$ (fine-structure constant) appears since G-forbidden transitions require that the decay proceed via electromagnetic interaction.

The initial Dalitz plot analysis was performed by Bastien et al. [34] based on 23 events shown in Figure 19. They argued that the 3 $G = -1$ possibilities are unlikely because of the absence of zeros in the population density in places predicted by the relevant matrix elements. Of the three $G = +1$ assignments, $0^+$ appears most likely and would indicate some final state interaction which would enhance the low $T_{\pi^0}$ part of the plot.

The conclusive evidence that $J^{PG}$ is indeed $0^+$ for $\eta$ meson was provided by the observation of $\eta \to 2\gamma$ decay made by Chretien et al [36]. They have studied $\pi^0p$ interactions in a 50 liter methyl iodide bubble chamber with a radiation length of 8.2 cm. Thus conversion probability of the $\gamma$ rays was very high. Events were selected which had no additional prongs at the interaction vertex and two converted $\gamma$ rays. The $\gamma$ momentum vectors were transformed to the $\pi^0p$ rest frame and the opening angle between the $2\gamma$'s calculated. This distribution, for $2\gamma$ ray decay, is uniquely determined by the mass of the parent particle. The final plot, with background subtracted, is shown in Figure 20 and provides convincing evidence for the $\eta \to 2\gamma$ decay mode.

![Normalized Dalitz plot of the $3\pi$ system for 23 of the 27 observed $\Lambda\pi^+\pi^-\pi^0$ events. The four events with $M_{3\pi}<530$ MeV were interpreted as background and excluded. Three or four of the remaining events are probably also background. Charge-conjugation invariance allows us to fold the plot about the $T_{\pi^0}$ axis (from Ref. 34).](image)
2.5. \( \phi \) Meson

The \( \phi \) meson was first observed by a Brookhaven-Syracuse group \[37\] studying the reactions

\[ Kp \rightarrow \Lambda K^0 K^0 \]
and \[ Kp \rightarrow \Lambda K^+ K^- \]

at 2.24 and 2.5 GeV/c in the BNL 20" hydrogen bubble chamber. The Dalitz plot and the projection on the \( M^2(\Lambda K^0 K^0) \) axis are shown in Figure 21. There is clearly a peak very close to the value of \( 2m_K \).

Initially there was some possibility that this effect was a manifestation of an S-wave final state \( \Lambda K \) interaction which was studied in some detail by the Berkeley group \[38\] in the reactions

\[ \pi p \rightarrow K\bar{K}N. \]

However, additional statistics from the Brookhaven experiment \[39\] enabled one to rule out that possibility and obtain a determination of the quantum numbers of this resonance. The main argument relied on the fact that depending on the value of its charge conjugation quantum number, \( C \), a state could decay either into \( K_S^0 K_L^0 \) state (for \( C = -1 \)) or into a \( K_S^0 K_L^0 \) or \( K_S^0 K_L^0 \) state (for \( C = +1 \)) \[40\]. In the BNL experiment 23 events were found with only one visible \( K_S^0 \) and none with two \( K_S^0 \)'s clearly demonstrating the validity of the \( 1^- \) assignment.

Precise width of the \( \phi \) was obtained shortly afterwards by the Columbia-Rutgers group \[41\] by looking at

\[ \bar{p}p \rightarrow \phi \pi^+ \pi^-, \phi \rightarrow K^+ K^- \]

with both \( K \)'s stopping in the chamber. The measured width was \( \Gamma = 3.1 \pm 1.0 \) MeV.
2.6. \( A_2 \)

I would like to conclude discussion of different meson states with the story of the \( A_2 \). There have been early indications [42] of a possible 3\( \pi \) peak in the 1.0 to 1.4 GeV mass region from heavy liquid bubble chamber work. The first evidence that this effect was due to a \( \pi \rho \) resonance was obtained by G. Goldhaber et. al. [43] by studying reactions

\[
\pi^+ p \rightarrow \pi^+ \pi^- \pi^+ p \\
\pi^+ p \rightarrow \pi^+ \pi^- \pi^+ \pi^0 p \\
\pi^+ p \rightarrow \pi^+ \pi^- \pi^+ \pi^- n
\]

at 3.65 GeV/c in the BNL 20° HBC. The first of these reactions showed a large cross section for \( \rho \) production and the subsequent analysis of the three body channel

\[
\pi^+ p \rightarrow \rho^0 \pi^+ p, \rho^0 \rightarrow \pi^+ \pi^-
\]

indicated a broad enhancement in the \( \pi \rho \) mass squared spectrum between 1.0 and 2.0 GeV\(^2\) (Figure 22).

The broad enhancement was resolved into two separate peaks by two different groups, one in Berkeley [44], the other one in Europe [45], both publishing simultaneously. The Berkeley data came from the analysis of 3.22 GeV/c \( \pi^+ p \) interactions in the 72° bubble chamber. The events fitting the hypothesis

\[
\pi^+ p \rightarrow \pi^+ \pi^- \pi^- p
\]

showed a strong \( \rho \) peak in those events which do not show evidence for production of \( \Delta (1232) \). In the 3\( \pi \) mass distribution two clearly resolved peaks are seen as shown in Figure 23b, and they are both associated primarily with \( \rho^0 \pi^- \).

The authors have also looked for final states

\[
\pi^+ p \rightarrow K^0 K_S^0 \rho \\
\pi^+ p \rightarrow K^0 K_S^0 \pi^- n.
\]

The mass spectrum of the \( K\bar{K} \) (Figure 23a) shows evidence for the higher peak only, giving additional independent support for the presence of two different states. Furthermore, since decay into \( \pi \rho \) implies \( G=-1 \), and for \( K\bar{K} \) system \( G=(-1)^{J+T} \), the allowed spin parity assignments [43] are \( J^P = 0^+, 2^+, 4^+, \) etc. Since the observation of 3\( \pi \) decay mode excludes \( 0^+ \), \( J^{PG} = 2^- \) is the lowest possible quantum number assignment. The authors chose to call the second state \( R \) meson, following suggestion of Pignotti [46] who previously presented an argument for the existence of a \( 2^- \) octet.

The European collaboration studied the reaction

\[ \pi^+ p \rightarrow \pi^+ \pi^- \pi^- p \]

at 4 GeV/c. Again, strong \( \rho \) and \( \Delta (1232) \) production have been observed. The analysis focused on those events when \( \Delta (1232) \) is not produced. The \( \pi^+ \pi^- \pi^- \) mass spectrum for those events shows clearly two peaks (Figure 24), at 1.08 GeV and at 1.32 GeV. A plot of similar spectrum (not shown) where neither \( \pi^+ \pi^- \pi^- \) combination is in the \( \rho \) region does not exhibit those peaks. The authors called the peaks \( A_1 \) and \( A_2 \) and these names were subsequently accepted by other workers in the field.

![Figure 22. The \( M^2 (\rho^0 \pi^+ \pi^- \pi^- p) \) distributions for \( \Delta^2 \) values less than (a) and greater than (b) 50 \( m_{\pi^2} \) (from Ref. 43).](image-url)
Figure 23. Effective-mass distributions for (a) $K^+K^{*0}$ and $K^0\bar{K}^*$ pairs; (b) $\pi^+\pi^-\pi^-$ combinations for events with $M(\pi^+p)$ outside the $\Delta^{++}$ interval. The lower curve represents $3\pi$ phase space normalized to events outside the peaks (from Ref. 44).

This collaboration also looked for presence of structure in the $\pi\eta$ mass spectrum from the process $\pi^+p \rightarrow p\pi^+\eta$

and observed indications that both $A_1$ and $A_2$ were present. This would require $J^P$ assignment of $1^-, 2^+, 3^-$, etc., for both states, consistent with the conclusion of the Berkeley group for the second peak.

The $A_2$ situation became more complicated with the publication of evidence for two peak structure in the $A_2$ region by G. Chikovani et al. at CERN [47]. They used a missing mass spectrometer which relied solely on precise measurement of the momentum and angle of the recoil proton and momentum of the incident $\pi^+$, nominally 7 GeV. The proton momentum was initially measured by time of flight; range measurement was added for the second part of the data taking period. The spectrometer's aperture was rather limited and was centered on the Jacobian peak for the $A_2$ region, from 44.5° to 66.8°.

Figure 24. $\pi^+\pi^+\pi^-$ effective mass distribution for reaction $\pi^+p \rightarrow p\pi^+\pi^-$, with both $p\pi^+$ masses outside the $N^*$ region. The curve shows a superposition of a smooth background and two Breit-Wigner distributions normalized to the histogram (from Ref. 45).

In this experimental arrangement, the counting rate was maximized and the sensitivity of the missing mass to uncertainty in the proton energy minimized. Clearly the statistics obtained for this very limited kinematic region were much higher than one could ever hope to obtain in a bubble chamber experiment. Thus the experiment could never be reproduced exactly in a bubble chamber. The big shortcoming, of course, was that no information at all was obtained about the final state resulting from the decay of the reported $A_2$ state.

The experimental resolution varied somewhat depending on the range of the recoil proton, from a low of $\Gamma_{\exp}$ (full width) = 16 MeV to $\Gamma_{\exp} = 28$ MeV. When the spectrum is divided into five range bins, dips are seen at the center of the peak in the three range bins with the best mass resolution (16-20 MeV). The data from the latest experiment were combined with those obtained earlier at both 6 and 7 GeV with a somewhat different missing mass spectrometer [48]. Because of the uncertainty in the absolute mass scale calibration, the scale was adjusted for the two sets of data so as to give the same value for the center of the $A_2$ peak. The combined data are shown in Figure 25.

The data were fitted to three different hypotheses: single peak, two independent peaks and a dipole with a symmetric two peak structure. The last two hypotheses gave equally good fits but the first one gave a confidence level of only 0.1 percent.
Figure 25. $A_2$ data from the 1965 and 1967 runs. The superimposed fits are: 1) a single Breit-Wigner curve (dashed line); 2) two incoherent Breit-Wigner curves (dotted line); 3) a “dipole” (full line). Note the suppressed zero (from Ref. 47).

A variety of subsequent experiments tried to reproduce these results. The bubble chamber experiments could look in detail at various final states resulting from the $A_2$ production with very good resolution but with relatively limited statistics. The results from those experiments were somewhat contradictory, some finding no evidence for double peak structure [49], others supporting [50] the results of Chikovani et.al., at least in some subsample of data. These results, of course, were not directly comparable to the original experiment because they looked over all production angles and frequently only at some specific final states. Other counter experiments [51] addressing this issue were also performed and they gave somewhat contradictory results. None of these experiments directly reproduced the conditions of the CERN experiment.

The issue was not resolved until a Northeastern-Stony Brook group [52] performed an experiment similar to CERN’s, by studying the same kinematic region with a missing mass technique and with comparable or better mass resolutions which could be independently verified by looking at $\pi^+p$ elastic scattering. Data were taken with 5 GeV $\pi^+$ and $\pi^-$ beams and a 7 GeV $\pi^-$ beam. A variety of fits were made and they all favored the single Breit Wigner hypothesis over a dipole fit by more than four standard deviations. The split $A_2$ was finally put to rest.

The $A_2$ story illustrates the strength but also the limitations of the bubble chamber technique. The split $A_2$ controversy was both started and ended by a counter technique; bubble chambers were not able to make a definite statement on this issue. The limitation was fundamentally one of the statistics; if one needed to investigate a limited region of phase space, one had to accumulate large statistics in that limited region; bubble chambers were not capable of doing that. On the other hand by 1970 one was able to design and construct an experiment with electronic techniques which could accumulate a large amount of data in a limited region of phase space; bubble chambers could not compete in this area.

CONCLUSION

As I hope this review demonstrates, the first five years of the 1960’s were truly a golden age of bubble chambers in the field of meson resonances. Many contributions in that area were also made in the second half of that decade by experiments utilizing this technique, but they were not as revolutionary and no longer had practical monopoly on the field; experiments with electronic techniques were beginning to play larger and larger roles as indicated partly by the $A_2$ story.

Even subsequently to 1970, bubble chambers continued to play an important role in high energy physics. To a large extent it was made possible by extending and improving the bubble chamber technique: rapid cycling chambers, triggered flash lights, external particle identifiers, internal high Z plates, mixtures of liquids, and high resolution cameras, all played a significant role in extending the useful life of bubble chambers and enlarging the scope of investigations which were possible with this technique. And of course one cannot neglect the
important role that large bubble chambers played in the initial exploratory investigations of neutrino physics at all new accelerators.

On the whole, however, after 1970 bubble chambers played a relatively minor role in the field of meson resonances. What were the reasons for this development? Three obvious reasons come to mind.

Firstly, studies of higher lying multiplets required significantly larger statistics than could be obtained with bubble chambers. This was caused at least in part by the need to do detailed partial wave analyses of final states.

Secondly, the electronic techniques made incredible advances during the latter half of the 60's and the 70's. Track reconstruction was revolutionized by successive inventions and developments of spark chambers, proportional chambers, and drift chambers. Simultaneously, advances in electronics and computing allowed one to take full advantage of these wire chamber techniques and also provide other measurements (like calorimetric energy measurement) that bubble chambers were not able to do. The advances in bubble chamber technology simply could not keep up with these revolutionary developments.

Finally, the focus of interesting physics shifted gradually from fixed target experiments to the colliders. Already in the late 60's e⁺e⁻ colliders were able to provide important and unique information on the widths of the vector mesons resonances and on their branching ratios into charged lepton pairs [53]. e⁺e⁻ colliders could be tuned to energy corresponding to a mass of a vector meson and thus could provide a wealth of data on that particle. In addition, the mesonic states containing heavy quarks, charm or bottom, could be produced most effectively at the colliders. The bubble chamber technique, however, was not suitable as a detector in a collider environment.

The Livingston plot for accelerators illustrates that acceleration technologies eventually become obsolete as higher energies are sought and eventually need to be replaced by new methods of acceleration if further progress is to be made. The same has happened to bubble chambers as they became replaced by more powerful detector techniques. On the other hand, the general methodology (and associated philosophy) of bubble chambers lives on in the current 4π detectors at the colliders, especially the e⁺e⁻ colliders. These detectors exemplify the original bubble chamber philosophy of recording all events (on tape rather than on film), providing a 4π coverage, and analyzing the events subsequently.

The modern day analysis techniques recognize the power of seeing the events and quite a bit of effort has gone into producing event displays that would accomplish this. In bubble chambers we have gone from a visual picture on film to digitized data; in electronic detectors, we reconstruct a visual image of event on a computer terminal from primary digital data. Thus one of the main strengths of the bubble chambers, ability to see the unexpected, has been recreated in the current electronic detectors.

References

23. Y. Nambu, Ref. 4.

