BROOKHAVEN NATIONAL LABORATORY

CONF-880889--9

September, 1988 BNL-41936

THE SEARCH FOR SCALAR MESONS*

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BNL--41936

DE89 002937

ABSTRACT

The search for I=0 0^{++} mesons is described. We highlight the crucial role played by the states in the 1 GeV region. An analysis program that with unimpeachable data would produce definitive results on these is outlined and shown with present data to provide *prima facie* evidence for dynamics beyond that of the quark model. We briefly speculate on the current status of the lowest mass scalar mesons and discuss how experiment can resolve the unanswered issues.

*Invited talk at the BNL workshop on glueballs, hybrids, and exotic hadrons (August 29-September 1, 1988).

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The study of hadron spectroscopy is the only way of learning about the confinement mechanism of QCD and the search for scalar mesons with I=0 $J^{PC} = 0^{++}$ is an essential aspect of this, elucidating the nature of the QCD vacuum. As is well known, QCD suggests that the spectrum of hadrons is far richer than that in the naive quark model and that even in a world without quarks there would exist hadrons corresponding to gluonic excitations of matter. It is the search for these that has dominated spectroscopy for the past ten years. The obvious place to start the search for glueballs is in channels with vector and tensor quantum numbers, because there we already know the lowest mass meson multiplets and have found that they have ideally mixed quark configurations. This knowledge provides us with a firm foundation for searching for dynamics beyond that of the quark model. This would be signalled by the discovery of states additional to the conventional nonets and a lone isoscalar would be an obvious glueball candidate.

However, in the case of scalar mesons, though rumour has it that the next Particle Data Tables [1] will list many states :

$$\begin{aligned} &f_0\,(975)\,, f_0\,(1240)\,, f_0\,(1300)\,, f_0\,(1590)\,, f_0\,(1730)\,, \\ &f_0\,(1755)\,, f_0\,(900)\,, f_0\,(988)\,, f_0\,(991)\,, f_0\,(1430) \end{aligned} \tag{1}$$

[and we have even heard at this meeting that the θ may not just be the $f_2\,(1720)$, but an $f_0\,(1720)$ too [2] and of a scalar $f_0\,(1530)$ from LASS [3]], we do not know which of these completes the lowest quark model multiplet, never mind which are four quark states, hybrids, $K\bar{K}$ molecules and what's left over to be glueballs. Though we can all select some of these states and stir them in our favourite quark mixing pot and cook up a respectable multiplet, such an exercise begs the question " what are the many states in this list we have left out ?". One is forced to conclude that we cannot reach any definitive conclusion about the parton make-up of any of these states and to what multiplets they belong until we can reach definite conclusions about which of these many f_0 states actually exist, which are distinct, what their parameters are and to which channels they couple. Anything else must be mere speculation at present. So I want to discuss how we can attempt to resolve these issues. The reason for the confusion is partly experimental, as I'll touch on shortly, but perhaps more importantly dynamical. For nowhere is the dynamics of resonances more complicated than in the scalar sector. While such complications as increasing overlap will eventually occur in all quantum numbers, nowhere does this already happen at so low an energy, as I will discuss. Since here we shall only be concerned with states of the same J^{PC}, it will be easier to discriminate between these by using their old names, like ϵ, S^*, rather than the generic f_0. I shall therefore use old and new names interchangably as seems appropriate.

Now how do we learn about scalar states ? They couple largely to pseudoscalar channels $\pi\pi, K\bar{K}, \eta\eta$, etc. and so let us first consider the $\pi\pi$ channel to which we expect all the f_0 states of eq. (1) to couple. From dipion production, initiated by pion beams, at high energies and small momentum transfers, we can deduce the cross-section for reactions like $\pi^+\pi^- \to \pi^+\pi^-$, a cross-section with prominent peaks [4] corresponding to the spin 1, 2, 3 and 4 states lying along the leading Regge trajectory. What we are interested in here is the S-wave component underneath all these. Since this is never more than 1/4 of the total, it means we must have high statistics to separate out the S-wave contribution. Of course, we separate this component, not from the integrated cross-section, but from the angular information, which measures the interference between the S-wave, for instance, and the dominant waves. Thus at lower energies (up to say 1 GeV), where there is interference with the P-wave, the S-wave component can be reliably separated and, with data on other charged channels, the I=0 contribution abstracted. However, as one goes up in energy, even with infinite statistics, ambiguities intrude. This means that the same experimental data can be described exactly by a number of different amplitudes and these will have different spin decompositions. While the leading waves will always be more or less the same, inevitably the S-wave will be the most affected. Without extra theoretical input or data on polarized targets, such ambiguities remain and limit our ability to extract the S-wave in $\pi\pi \to \pi\pi$ to below 1.6 GeV at present. Of course, channels with higher thresholds, like $\eta\eta$, postpone such ambiguities till somewhat higher energies and this is to their considerable advantage.

Now having abstracted the I=0 S-wave $\pi\pi$ elastic cross-section from the raw data, what do we expect to learn from this ? What we want to study is the spectrum of hadrons with these (vacuum) quantum numbers, because we believe this to be a direct reflection of the underlying dynamics between the constituents of matter. Such resonant states are naively expected to produce a peak in some measured cross-section, the parameters of which (its position and height) tell us about the nature of the state. This is based on the idea that the cross-section is described by some amplitude, which itself is described by some simple Breit-Wigner form. Such a Breit-Wigner form has a pole in the complex energy plane, the position of which on the nearby unphysical sheet tells about the mass and width of the state and the residue of this pole tells us about its couplings to the particular channels involved. Importantly, it is these parameters of the poles of the S-matrix that are the basic dynamical entities, because it is only poles of the S-matrix that universally transmit from one process to another. However, in the case of an isolated resonance, one isolated from all other dynamical features – that is in the absence of overlapping resonances or strongly coupled thresholds – then there is a one-to-one correspondence between the basic dynamical entity, which is the pole in the complex energy plane, and what one observes in experiment. In general, there need not be. Even dips in cross-sections can correspond to poles of the S-matrix as nowhere better seen than in scalar channels.

Knowing what we are looking for, namely the poles in the complex energy plane, let us now examine the $\pi\pi \to \pi\pi$ S-wave cross-section. This is shown in fig. 1. We see it has no narrow bumps, but rather a broad enhancement from $\pi\pi$

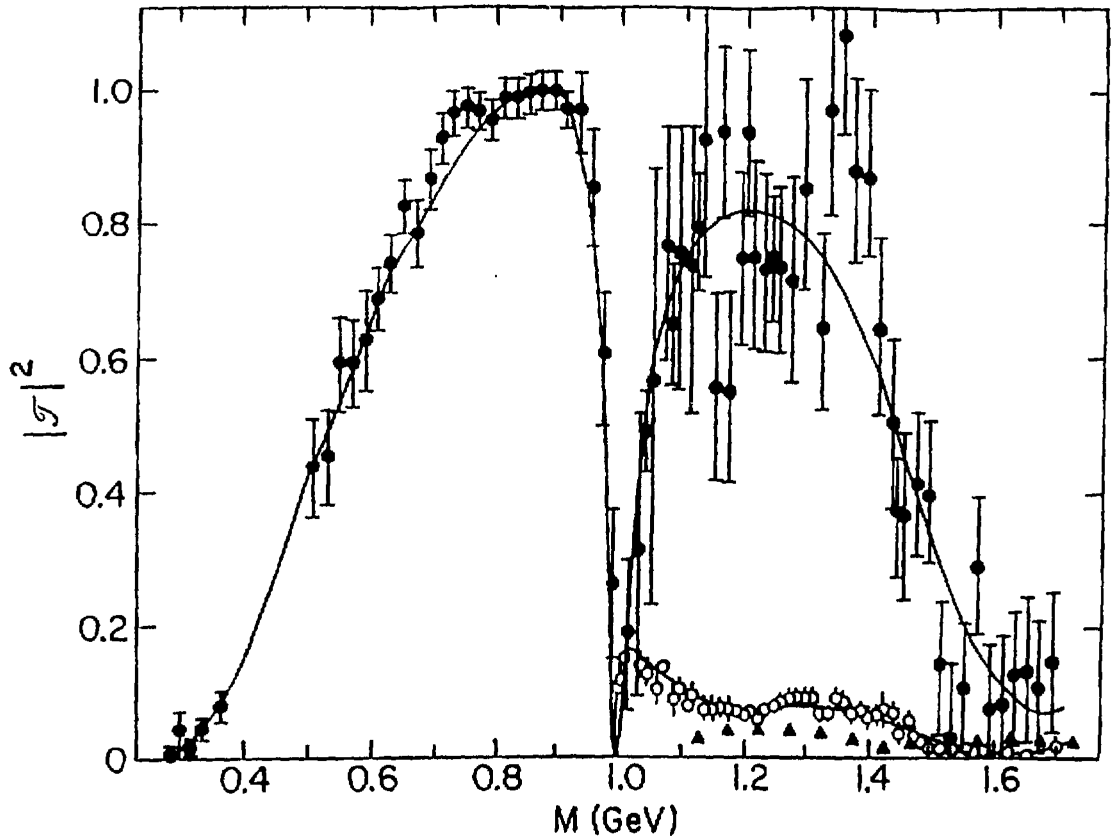

Fig. 1 : I=0 S-wave cross-section scaled by a factor of E^2. In fact, $|\mathcal{T}|^2$, is plotted, where $\mathcal{T}$ is the S-wave amplitude. The solid dots are for $\pi\pi \to \pi\pi$, the open circles for $\pi\pi \to K\bar{K}$ from the compilation of data referenced in AMP [5] and the triangles for $\pi\pi \to \eta\eta$ from GAMS [6].

threshold up to 1 GeV and then another from 1.05 to 1.6 GeV and though one can surely fit this with half a dozen Breit-Wigners it should be clear that this is a meaningless thing to do. Notice the onl narrow structure is the deep dip near 1 GeV. All this has been known for moe than fifteen years. Of course, $\pi\pi$ is not the only channel in the world, $\pi\pi$ cango to $4\pi, 6\pi, 8\pi, K\bar{K}$, etc etc. Now, though the 4π channel starts at 560 MeV, xperiment tells us that such multi-pion channels are negligible until we get upo 1.2 GeV or so where $\rho\rho$ threshold starts to open up. This means that the fit significantly coupled open channel is the $K\bar{K}$ one and the $\pi\pi \to K\bar{K}$ cross-ection is shown in fig. 1. too. Notice that it opens very sharply and is clearly orrelated with the dip in the elastic contribution. This points to a dynamical feature in the neighborhood of 1 GeV that couples strongly to $K\bar{K}$, otherwise the inelastic cross-section would not rise so rapidly [7]. As we go up in energy other thresholds open up, for instance $\eta\eta$, shown in fig. 1, as measured by the GAMS group [6]. This is overtaken by the multi-pion channels beyond 1300 MeV.

Armed with these data, we now want to determine the underlying amplitudes and then the poles of the S-matrix. To do this, we clearly need to know, not just the moduli of the amplitudes, but their phases as well. It is here that the very important property of the conservation of probability enters for the first time in this talk. The requirement that we cannot get more out in a scattering process than we put in means that the S-matrix is unitary and this in turn imposes a severe constraint on all amplitudes. This is most readily expressed in terms of amplitudes with definite spin and isospin, like the isoscalar, scalar one we consider here. Denoting these by $\mathcal{T}$, unitarity requires :

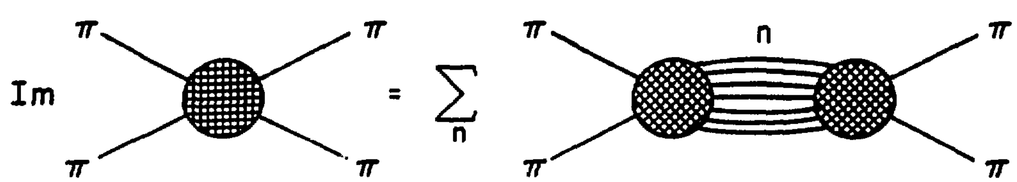

Fig. 2 : Unitarity condition for $\pi\pi \rightarrow \pi\pi$ amplitudes with definite I and J.

where the sum is over all kinematically allowed intermediate states. Now in the case of $\pi\pi$ scattering below $K\bar{K}$ threshold, there is effectively only one channel that can contribute – the $\pi\pi$ channel itself. This greatly simplifies the relationship and says :

$$\mathcal{T}\,(\pi\pi \rightarrow \pi\pi) \quad = \quad \sin\delta\; e^{i\delta} \qquad (2)$$

so knowing the modulus, we know the phase and vice versa. This is, of course, known to all graduate students. As we go up in energy, when other channels contribute, unitarity is just as powerful a constraint, it's just more difficult to implement, because it inter-relates many different processes. Using eq. (2) and its generalisation above inelastic threshold, we can determine from the cross-sections of fig. 1, what the elastic $\pi\pi$ amplitude is doing. This is conveniently displayed in the Argand plane in which the axes are the real and imaginary parts and the labels in fig. 3 show the energies in GeV. Below inelastic threshold, eq. (2) means the amplitude $\mathcal{T}$ traces the circle shown in fig. 3. This plot points to a minimum of two dynamical features in this energy region. To see this, let us, for the moment, ignore the rapid dip in the cross-section in the region of the $K\bar{K}$ threshold. Then the first dynamical entity, in fig 3, gives the steady increase of the phase up to roughly 90 degrees at 900 MeV and then continues round on the inside track up through 1300 MeV. This broad structure, which governs the bulk of the elastic cross-section in fig. 1 has variously been ascribed to an ϵ or σ at 600 MeV and then 900 MeV and latterly 1300 MeV. These differences corresponding to different definitions of what a resonance's parameters are. As we have stressed, there is only one uniquely meaningful definition, the pole in the complex energy plane, to which we shall return. The only thing to note is that there is a broad structure straddling the region from 600 to 1300 MeV, which is largely elastic, and gives most of the elastic cross-section seen in fig. 1. This is not describable by any simple Breit-Wigner, not just because it is so broad, but because on top of it sits another dynamical structure with a strongly coupled open threshold. This is responsible for the deep dip in the elastic cross-section and rapid onset of $K\bar{K}$ threshold. This is seen in the way the amplitude in fig. 3 plunges from the top of the unitarity circle, leaves the circle at K^+K^- threshold, lurches into the center of the circle and rises back up to the top – all within some 150 MeV. This is what is known as the S^*. Though this [7] has been around since the early 70's, what the nature of this state is is still uncertain. One reason for this is that its parameters and couplings [8] are determined by exactly where the elastic amplitude of fig. 3 leaves the circle and how it passes through the 1 GeV region. As illustrated in fig. 3 the experimental uncertainties are largest there (see fig. 1) – the $\pi\pi$ elastic S-wave amplitude being small and determined from its interference with a P-wave that is also small. Thus to determine exactly what is going on in this all-important region, we need more information, than that in fig. 1.

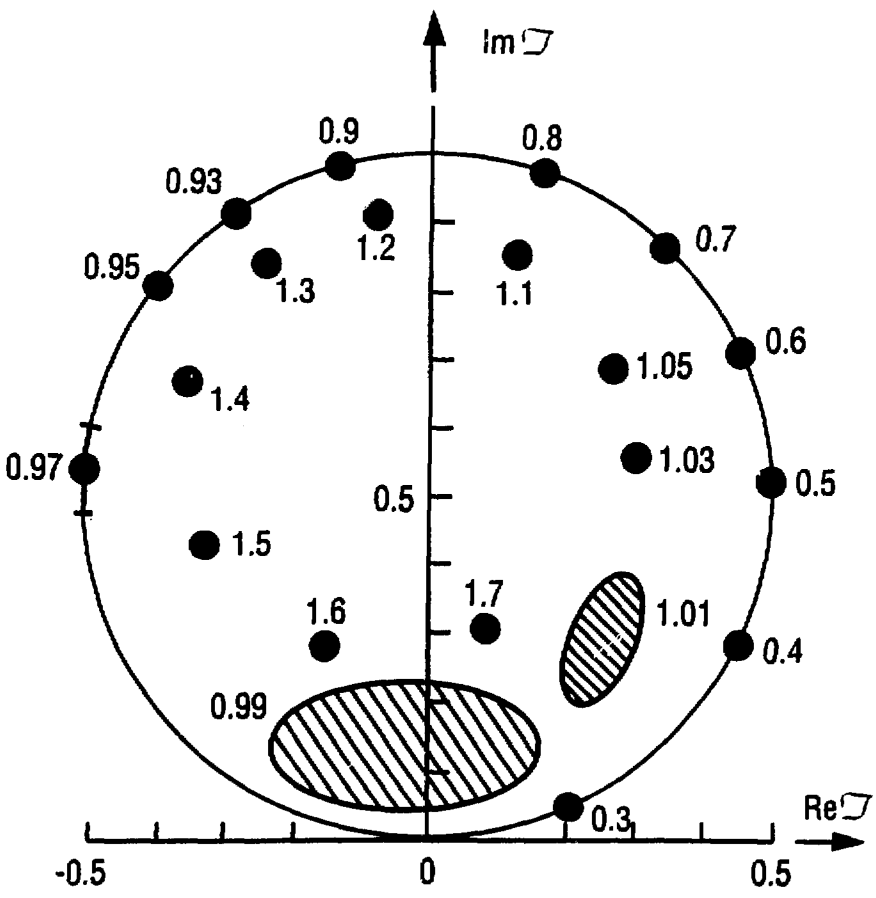

Fig. 3 : The complex I=0 $\pi\pi \rightarrow \pi\pi$ S-wave amplitude, $\mathcal{T}$, in the Argand plane. At each energy labelled, the amplitude is a vector from the origin to that point. The experimental errors are shown only in the $K\bar{K}$ threshold region. Below that region and just above the uncertainties are small. At higher energies, like 1.6 GeV, see Refs. 6,9 for a plot of the errors, which are again large.

One of the beauties of $\pi\pi$ final states is that, being the lightest of all multi-hadron configurations, they are the outcome of many processes : $\gamma\gamma \to \pi\pi$, $\psi \to \phi\pi\pi$, central dipion production in $pp \to pp\pi\pi$, etc. Remarkably, unitarity relates all these to the $\pi\pi$ elastic amplitude too, in a most important way. Consider, the process $AB \to \pi\pi$, with amplitude $\mathcal{F}$, where neither A nor B has any (significant) strong interaction with the pions, then unitarity requires the constraint of fig. 4. Once again, below the inelastic threshold, (effectively 987 MeV), $\pi\pi$ intermediate states are all that can contribute and so we have

$$\mathrm{Im}\,\mathcal{F}\,(AB \to \pi\pi) \quad = \quad \mathcal{F}^*\,(AB \to \pi\pi)\ \mathcal{T}\,(\pi\pi \to \pi\pi) \tag{3}$$

This sets no constraint on the size of the amplitude $\mathcal{F}$, unlike eq.(2) for the wholly strong interaction amplitude $\mathcal{T}$, but it does require that the amplitudes $\mathcal{F}$ and $\mathcal{T}$ have the same phase. It means that the quotient of $\mathcal{F}$ and $\mathcal{T}$ is a real function. In the presence of other channels, this relationship generalises to

$$\mathcal{F}\,(AB \to j) \quad = \quad \sum_i \alpha_i\ \mathcal{T}\,(i \to j) \tag{4}$$

where crucially the functions α_i, which are the couplings of channel AB to final state i, are real for $E > 2m_\pi$, ensuring that the amplitudes $\mathcal{F}$ and $\mathcal{T}$ have the same right hand cut structure, as unitarity requires.

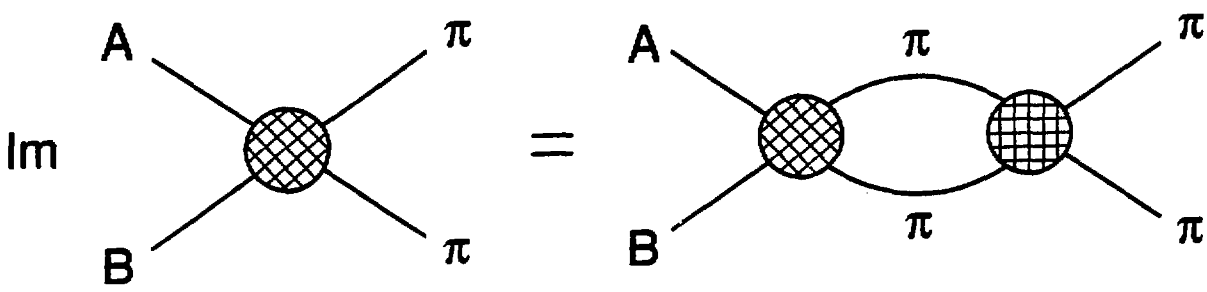

Fig. 4 : Unitarity condition for $AB \to \pi\pi$ in the energy region below the first inelastic threshold, effectively 1 GeV.

Now, what does this do for you in practice ? It ensures, for instance, that the ρ you see in $e^+e^- \to \pi^+\pi^-$ is the same ρ you see in $\pi\pi$ elastic scattering –

the pole in the corresponding S-matrix elements must be the same. It ensures that $\pi\pi$ dynamics in the decays of heavy quarkonia like $Q' \to Q\pi\pi$, where $Q = \Upsilon(1S), \Upsilon(2S)$ and J/ψ, must all be related and this should not be forgotten [10]. For our present purpose, the highest statistics data on $\pi\pi$ final states, which have been separated into their partial wave components, is that on central dipion production in $pp \to pp\pi\pi$ from the AFS collaboration at the ISR [11]. This is known as "the ISR glueball search experiment". As the two protons approach each other at high energies, each is a collection of quarks, surrounded by a cloud of gluons, and the dominant scattering mechanism is that a colour singlet bit of glue is transferred from one to the other. This is known as pomeron exchange. Since this is the most probable process of all giving the bulk of the 50 to 80 mb at collider energies, we can imagine that once in awhile, a colour singlet bit of glue gets detached from one proton and a similar piece from the other and that these fuse together to form some low mass glueball state that subsequently decays into pions, kaons, etc, that you detect. This at least is the basic idea. The kinematics of the experiment ensure that the most of the huge momentum at the ISR continues with the on-going protons and that the mesons formed in the final state are well separated in rapidity from these. This allows us to think of the process as pomeron-pomeron$\to \pi\pi, K\bar{K}, ...$ We do not need to know the nature of the pomeron, only that it carries the quantum numbers of the vacuum and that the process is factorised in rapidity. This ensures that the 2π cut structure must be that of $\pi\pi$ elastic scattering and that the amplitude obeys eqs. (3,4). Despite the motivation for this search, unitarity says that this experiment cannot produce any state that cannot appear in $\pi\pi$ elastic scattering. In terms of partons, unitarity for hadrons doesn't care whether you get to the final state pions through a quark or gluish initial state. All scattering processes occur that are kinematically allowed and quarks turn into glue and vice versa. Nevertheless, such data can with their precision address the issue of the structure of the related S-matrix elements. This would be true of data on any non-strongly interacting channel with $\pi\pi$ final states. It is just that these data have 100,000 events and as illustrated in fig. 5a track through the crucial 1 GeV region far more precisely than the meson-meson scattering data do or perhaps ever will and have information on the coupled $K\bar{K}$ final state too.

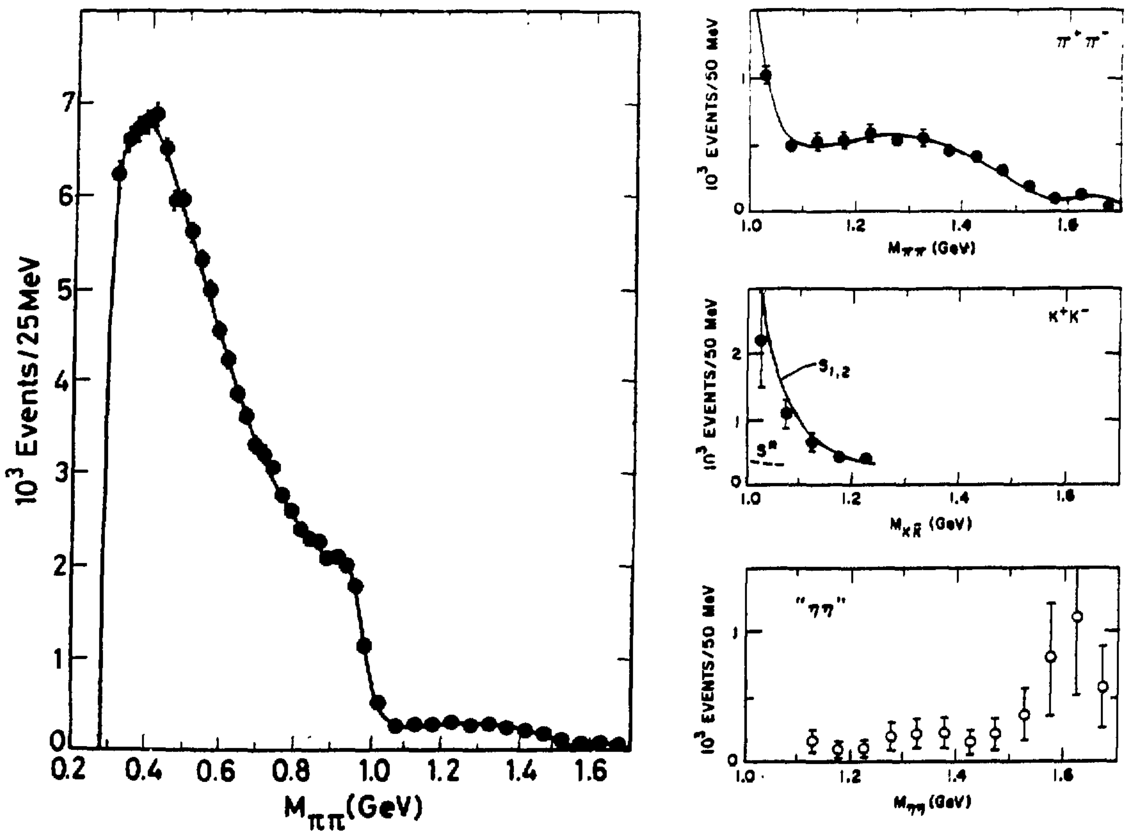

Fig. 5 : Mass spectrum of centrally produced S-wave dimeson events in $pp \to pp\,(MM)$ corrected for acceptance. (a) $\pi\pi$ spectrum from the Axial Field Spectrometer collaboration [11] at the ISR with $\sqrt{s} = 63$GeV ; (b) $\pi\pi, K\bar{K}$ spectra above 1 GeV from the AFS collaboration [11], and for $\eta\eta$ inferred from the GAMS results [12] on central production in πN scattering at 300 GeV/c. On the $K\bar{K}$ plot is shown [13] the effect of changing the S_1, S_2 scenario of AMP (which give the solid curves through the data) to the standard S^* (dashed line) just above 1 GeV.

It was therefore the aim of the AMP analysis [5] by King-Lun Au, David Morgan and myself to fit essentially all the high statistics data on the classic meson scattering processes

$$\pi\pi \to \pi\pi, K\bar{K}$$

together with these data on central

$$pp \to pp\pi\pi, K\bar{K}$$

in terms of amplitudes that automatically satisfy the constraints of coupled channel unitarity with parametrizations that in no way prejudge the number or nature of the underlying dynamical objects and to do this in as many inequivalent ways as possible so as to explore the full range of possibilities these data allow. With poorer data one is forced to fit results with simple Breit-Wigners and backgrounds added in arbitrary ways and let χ^2 decide how many states you have. But with high statistics results, we can (at least in a limited energy range, from $\pi\pi$ threshold up to say 1.1-1.2 GeV) allow experiment to speak for itself. The AMP analysis [5], for the cogniscenti, parametrizes the amplitudes in terms of both the K-matrix and the M-matrix with different mixtures of poles and backgrounds in each. A dozen different amplitudes were found in five classes of parametrization. All equally well describe the data. The quality of the fits can be judged from the curves in figs. 1, 5 here, and more extensively in Refs. 5,13. Having found these, each parametrized in different ways, the aim is to determine their poles in the complex energy plane. A quite remarkable thing happens. All the amplitudes have an identical configuration of four dynamical features – resonances. The pole-positions and residues differ surprisingly little from one of the five classes of parametrization to another. All are basically the same, making one believe that these are real. The positions and couplings are listed in Table 1.

If we think that the δ (now the $a_0\,(980)$) and the κ (now the $K_0^*\,(1350)$) are the I=1, $\frac{1}{2}$ members of a simple quark model multiplet, then we are looking for two isospin zero combinations to complete this nonet. Let us first interpret what we see, in Table 1, in terms of this – we can consider alternatives later. There is a broad ϵ at 900 MeV that straddles the whole region from 600 to 1300 MeV as expected, with couplings to $\pi\pi$ and $K\bar{K}$ that are like those of a quark model

Table 1 : I=0 S-wave resonances below 1.5 GeV from the AMP fits [5] ; their pole positions, E_R, and their residues in the $\pi\pi$ and $K\bar{K}$ channels, g_π and g_K respectively.

Resonance	$E_R\,(GeV)$	g_π (GeV)	g_K (GeV)
$\epsilon\,(900)$	$0.91 \ \ -0.35i$	0.52	0.27
$S_1\,(991)$	$0.991 - 0.021i$	0.22	0.28
$S_2\,(988)$	0.988	0.02	0.35
$\epsilon'\,(1430)$	$1.43 \ \ -0.20i$	0.58	0.16

state with just non-strange quarks. Remember, that these parton assignments are just mnemonics for their couplings to hadrons, which is, of course, all that such an analysis provides. Then at the top end of the experimental range that is fitted, and consequently the least reliable, is the $\epsilon\,(1430)$, to which we'll return. In a quark model picture, this would be naturally a radial excitation of the $\epsilon\,(900)$ and not in the same multiplet. Then comes the surprise. Instead of a single $S^*\,(975)$ we have in all our solutions two states. One, the $S_1\,(991)$ is a conventional resonance (again for the experts this means it has poles on more than one sheet of the complex energy plane) with a width of 42 MeV coupling to $\pi\pi$ and $K\bar{K}$ like a flavour singlet. The other, the $S_2\,(988)$ is a bound state (with a pole on only one sheet) of the $K\bar{K}$ system. It has a very small coupling to $\pi\pi$. In the quark model, this would naturally be an $s\bar{s}$ state, the ideal partner of the $\epsilon\,(900)$. This leaves the $S_1\,(991)$ as an obvious glueball candidate. Let me stress, that we cannot tell the parton content from the couplings to hadrons without further modelling. However, we can definitely conclude that in this extensive analysis we have three states in the 1 GeV region, when the naive quark model would lead us to expect just two. Whatever their nature, we have *prima facie* evidence for dynamics beyond that of the quark model.

It is natural to ask what is it about the data that requires the conventional S^* to be split into two objects. Of course, none of these resonances is described by simple Breit-Wigner forms, each overlaps with each other and with the strongly coupled $K\bar{K}$ threshold, so unlike a simple sum of Breit-Wigners we cannot trivially take one resonance out and still preserve the constraint of unitarity, which is so very important here. However, the AMP group [5] have shown that, at least in a limited energy region, the S-matrix elements can be written as products of quotients of Jost functions, which allows one to study the effect of replacing the S_1, S_2 by a single S^* at least around 1 GeV. What was shown was that the single [14] and double state scenarios both fit the classic meson scattering data equally well. That is no surprise. However, when the AFS central production data is included, the S_1, S_2 solution is overwhelmingly favoured over the single S^*. All the fits are much worse for the latter. The major discriminant [13] is the $pp \to ppK\bar{K}$ channel as shown in fig. 5b. Remember it is the data on the pomeron-pomeron channel to $\pi\pi$ that extrapolates through $K\bar{K}$ threshold more precisely than any other. For theorists, one can appeal to Levinson's theorem to support the claim that below 1.2 GeV there are three dynamical agencies — the way the $\pi\pi \to \pi\pi$ phase shift rises by almost 2π radians and the $\pi\pi \to K\bar{K}$ phase falls at $K\bar{K}$ threshold — see AMP [5] for a discussion of this.

How can we tell from experiment whether having three isoscalar, scalar states in the 1 GeV region is really true ? The first obvious objection is that there are other channels than $\pi\pi$, K^+K^- and K^0K^0 (since we are considering effects very close to $K\bar{K}$ threshold, the fact that the charged and neutral kaon channels have thresholds 8 MeV apart has been taken into account). As can be seen from fig. 6, it is clear that above 1300 MeV or so the $K\bar{K}$ channel certainly does not saturate the inelastic cross-section (which unfortunately is rather poorly determined by subtracting the elastic contribution from the total S-wave $\pi\pi$ cross-section, determined by the optical theorem). These sizeable differences, which are largely due to multi-meson channels – 4 and 6π and $K\bar{K}$

plus 1,2,3...πs – only affect the couplings of the ϵ(1430), as one would expect. Of course, we also know that there is the $\eta\eta$ threshold already at 1100 MeV. The cross-section for this has now been measured by GAMS [6]. As shown in fig. 1 this sets in relatively slowly. It can be explicitly checked that structures within a few MeV of 1 GeV cannot be affected by such a channel starting 100 MeV higher. Of course, it could be that channels like $\eta\eta$ are more important in central meson production. GAMS [12] have recently measured the central $\eta\eta$ cross-section in πN scattering at 300 GeV/c, in which their G(1590) state shows up so nicely. From the cross-section they quote for this and from the events they show down to $\eta\eta$ threshold, one can attempt to infer what the AFS experiment would have seen at their ISR energies if they had had neutral particle identification. The result is shown in fig. 5b. Though this extrapolation has been done very conservatively, each event in GAMS translates into hundreds of events in the "neutral AFS" and so care should be taken in interpreting the small GAMS statistics [12]. We again see that between 1.1 and 1.2 GeV, nothing untoward is happening. The $\eta\eta$ channel is not behaving anomalously and so, like the meson scattering reactions, can have little affect on the AMP conclusions in the neighbourhood of 1 GeV. Of course, real cross-sections on such inelastic channels in central production would be most helpful in checking this !

To proceed further up in energy, to go beyond the $K\bar{K}$ threshold region, up to where the GAMS G(1590) state is [6], requires a major new initiative, with added experimental input on the details of the increasing number of inelastic channels. Ron Longacre and the BNL/CCNY group have started such an ambitious program. They have explicitly included the $\eta\eta$ channel and lumped together the remaining inelastic final states. As reported at the KEK hadron spectroscopy meeting last year [15], they have fitted both the S- and D-waves. The inclusion of the D-wave is essential as one goes up in energy, since the major source of information about the phase of the S-wave is its interference with the D-wave and though at lower energies, below 1.3 GeV, the D-wave phase is

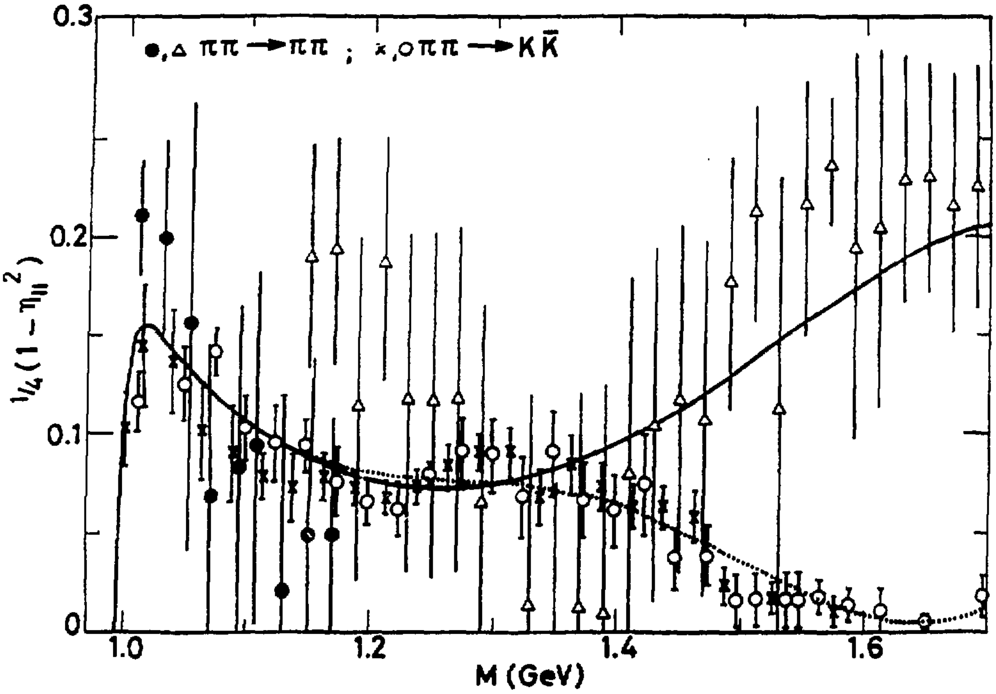

Fig. 6 : The cross-section for inelastic I=0 S-wave $\pi\pi$ scattering. This cross-section is proportional to $\frac{1}{4}\left(1-\eta_{11}^2\right)$, where η_{11} is the $\pi\pi$ inelasticity and it is this that is plotted. The solid dots and open triangles are the results on the total inelastic cross-section inferred from the elastic data, while the crosses and open circles are the $K\bar{K}$ contribution to this. References to all the data, are given in AMP [5], where the curves are also explained.

controlled by the very well-known $f_2\,(1270)$, above that resonance the details of the other contributions to the D-wave are important. Though the BNL/CCNY group [15] obtain excellent fits to the D-wave results, their S-wave amplitude, even with seven states, doesn't yet do very well in fitting the relevant cross-sections, particularly $\pi\pi \to \eta\eta$. Thus, they sensibly conclude it would be premature to enumerate the parameters of any of the many states they find in this scalar channel. As we heard at this meeting, this analysis, at least in a limited form, is continuing, and we await the outcome with interest. Such a treatment is essential to be certain of the nature of a state like the $G\,(1590)$. The difficulty in resolving the nature of such scalar candidates is illustrated by asking what we know up at 1.6 GeV about the crucial $\pi\pi$ cross-section, a channel to which they should all couple at some level (what level is what we need to know). Even adding the weight of fixed-t dispersion relations [9] to the highest statistics experimental results, the uncertainties in the S-wave amplitude up in the *G*-region would allow loops in the Argand plane (fig. 3) with elasticities from 0% to 15-20%. One should thus not under-estimate the task of going up to higher energies – even the AMP analysis with its very restricted channels took many man-years of effort.

There remains then the key issue of what is going on in the 1 GeV region. How many states are there and what is there nature ? These issues are crucial, since if the 1 GeV states are members of the lowest quark model multiplet, those at 1400 MeV must be radial excitations or four-quark states. But if the states around 1 GeV are something else then the lowest quark model multiplet may lie nearer 1400 MeV. It used to be commonly accepted that

$$\epsilon\,(900-1300)\,,\delta\,(980)\,,\kappa\,(1350)\,,S^*\,(975)\,, \tag{5}$$

now called f_0, a_0, K_0^*, f_0, formed a respectable quark model nonet [16]. It is clear dynamical effects must be far more important here than in the lowest mass vector or tensor multiplets, for the I=1 state and the largely $s\bar{s}$ isoscalar to be almost degenerate in mass, while the state with a single strange quark is so much heavier. The need for dynamical effects is not totally surprising. The strong $K\bar{K}$ coupling of the I=0, 1 states and the enormous width of the ϵ, κ indicate ideas based on a narrow resonance picture are too simplistic in the 0^{++} sector [17]. So the states of eq. (5) could form a reasonable nonet. Then the states at 1400 MeV would be candidates for radial excitations, hybrids, four quark states, etc.

Notwithstanding this, it could well be that of all the possible four quark configurations, only those in the $K\bar{K}$ mode naturally bind like molecules [18]. These would appear close to $K\bar{K}$ threshold and would have only I=0 and 1. It is certainly tempting to regard the $S^*\,(975)$ (or $S_2\,(988)$) and $\delta\,(980)$ as such a pair. This neatly explains their near degeneracy in mass. Inevitably, it leaves the broad $\epsilon\,(900-1300)$ and $\kappa\,(1350)$ out in the cold, with the $S_1\,(991)$ still an unattached scalar. However, we have heard at this meeting of an I=1 scalar state, coupling to $\pi\eta$, the $a_0\,(1350)$ reported by GAMS [19] and of an I=0 $s\bar{s}$ scalar under the $f_2'\,(1530)$ found by LASS [3]. It could be that it is these that form the lowest quark model multiplet

$$\epsilon\,(900-1300)\,,\delta'\,(1350)\,,\kappa\,(1350)\,,S^*\,(1530) \qquad (6)$$

in the old notation.

At present, eqs. (5,6) are just interesting alternatives for $q\bar{q}$ nonets : mere speculations without more experimental input. Moreover, we have the notion that there may well be extra states beyond those of the quark model, like the $S_1\,(991)$. Let us briefly turn to how we might be able to confirm some of these statements.

Let me tabulate some experiments that may usefully address these issues.

1) $\pi\pi \to \pi\pi, K\bar{K}$: i.e. more data on the classic meson-meson scattering. Such experiments are very unlikely to get support. However, the possibility of a $K\bar{K}$ bound state very close to the threshold predicts dramatically different behaviour for the cross-section for isoscalar, scalar $K\bar{K} \to K^+K^-$ and K_sK_s with their thresholds 8 MeV apart. Any experiment that could discriminate kaons down to threshold and in the charged channel was not swamped by the ϕ signal could resolve this matter !

2) $K^-p \to K_sK_s\Lambda$: this channel alone provides some valuable insight into this, since in the AMP analysis, for example, the $K\bar{K} \to K\bar{K}$ are not fitted but predicted. The LASS group [20] has measured this reaction in the kaon exchange region and remarkably found an enhancement very close to threshold – agreed with very small statistics – that favours a bound state rather than just the conventional S^*. This is an encouraging finding for the AMP analysis.

3) $pp\,(p\bar{p}) \rightarrow pp\,(p\bar{p})\,\pi\pi, K\bar{K}$: more data on central dimeson production would be very advantageous not only to confirm but to add to the AFS results [11] discussed earlier. To ensure they are dominated by pomeron exchange and consequently the final dimeson quantum numbers restricted to the I=0 $0^{++}, 2^{++}, \ldots$ quantum number sequence, data are needed at the highest possible energies, for instance at the CERN and Tevatron colliders, and with the smallest possible momentum transfers. Lower energy results, like those reported here from the WA76 collaboration [21] using the CERN Omega spectrometer have much the appearance of the AFS spectrum of fig. 5, but with significant non-vacuum quantum number contributions (presumably ρ exchange) that inevitably occur at 300 GeV/c with a wide momentum transfer interval. These would have to removed (by cuts in momentum transfer) and a moment analysis performed to get out the pure S-wave signal used in the AMP analysis discussed here. This may be possible and we urge the WA76 group to do this, particularly as they have results on the $K_s K_s$ channel too.

4) $\psi \rightarrow \phi\pi\pi, K\bar{K}$: data on these channels have long been available from Mark II [22]. In the $\pi\pi$ mode, the "S^*" is seen as a peak and indeed these data dominated the old PDG value [8] for the S* parameters. These data are, of course, equally well fitted by the S_1, S_2 scenario too. The much higher statistics data (in their preliminary form) from Mark III and from DM2 have also been fitted by the AMP group [5]. Data on such channels with angular separation (to really know the scalar component) would be a valuable input to an AMP-type analysis, rather than as here merely a check on the results of the amplitude package. Data on related channels initiated by Υ states would be equally helpful. However, to make use of unitarity to relate these decays to $\pi\pi$ and $K\bar{K}$ dynamics, it must be remembered that the analogues of the ψ and ϕ (the A, B of eqs. (3,4), fig. 3) in whatever decay must have no significant strong interaction with the dimeson final state.

5) $\phi \to \gamma S^* (S_1, S_2)$: radiative ϕ decays, except to π, η, have hardly been studied experimentally and would be a very important way of telling whether there was a $K\bar{K}$ bound state, since this would result in almost mono-energetic 30 MeV photons (their energy only being spread over the small ϕ width). Unfortunately, as computed by Close and Isgur [23], the branching ratios look rather small being $10^{-4} - 10^{-6}$ – the larger for a $K\bar{K}$ molecule rather than a $q\bar{q}$ or glue state. Nevertheless, such an experiment, perhaps at Novosibirsk, would doubtless aid our understanding of radiative decays.

6) $\gamma\gamma \to \pi\pi, K\bar{K}$. In principle, the two photon coupling of any state is a key pointer to its parton make-up. This coupling is related to the fourth power of the charge of the hadron's constituents and the modulus squared of the wavefunction of these at the origin. It is thus predicted to be quite different for a genuine $q\bar{q}$ state as opposed to a $K\bar{K}$ molecule or other four-quark configuration, as has long been emphasised by Ted Barnes [24] :

$$\Gamma\left(f_0\left(q\bar{q}\right) \to \gamma\gamma\right) \simeq 4.5\text{KeV} \quad ; \quad \Gamma\left(f_0\left(K\bar{K}\right) \to \gamma\gamma\right) \simeq 0.6\text{KeV}. \tag{7}$$

Thanks to the new much higher statistics two photon data with $\pi\pi$ final states from Crystal Ball [25] on the neutral channel and Mark II [26] on the charged one, with JADE and CELLO to come on these same reactions [27], it looks very likely that we will be able to test these possibilities. The analyses done uptil now [25,26,28] , which suggest that the scalar states in the 1 GeV region have $\gamma\gamma$ widths of tenths of KeV seem to point to a four-quark [29] or $K\bar{K}$ nature. However, these conclusions are based on simply fitting the data to Breit-Wigners and backgrounds. As emphasised time and again here, this is not appropriate for the scalar channel with its overlapping states. To perform a proper analysis one must include once again the constraints of unitarity that tie these final states to meson-meson scattering reactions, and one must also respect the gauge invariance of the two photon system [30]. Quite unlike a purely hadronic reaction, this requires that the I=2 $\pi\pi$ final state at low energies gives as big a contribution to the cross-section as the I=0. Indeed, the marked difference between the $\pi^+\pi^-$ and $\pi^0\pi^0$ cross-sections in the two photon process at low energy is because of the constructive and destructive interferences, respectively, between these I=0, 2 components. It is therefore crucial to take this into account in any analysis. A package to do this is presently being developed by David Morgan and myself [30], and I am reasonably hopeful that with data now being finalised, this may yield reliable results relevant to unravelling the mystery of the scalars. The search for scalar mesons, their nature and role in non-perturbative QCD is far from over.

ACKNOWLEDGEMENTS

It is a pleasure to thank King-Lun Au and David Morgan for a most rewarding collaboration and the Fulbright Commission for a travel grant for 1987/88.

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technical discussions were held. Only three of these vendors were convincing as to their capabilities to meet the requirements. Two of them responded to the RFQ. The contract was awarded to RCA. Their design was an advanced CMOS-SOS process in which all logic Cells had to be designed and simulated since no circuits in their Cell libraries could approach the speed requirement. The output circuit led to a patent. Many months of design reviews were held before a prototype run was attempted. In fact, the first three prototypes runs failed for a variety of reasons.

Early on in the project (before the contract was awarded) it was clear BNL had to take responsibility for all testing, even at the wafer level since the speed of this ASIC was more that an order of magnitude beyond RCA's in house test capability. This effort alone accounted for more that a man year of engineering and developement. The tester had to measure time to 100 ps, operate the chip from DC to 330 Mhz and exercise parameters for margin tests. All of this under software control and in a fraction of a second. The instrument was designed to test chips at the wafer level or as packaged parts.

After prototype runs yielded successful parts on the pilot line, the processing was moved into production facilities. Wafers were produced and returned to the pilot line for testing. Yields varied greatly. At one point 60 wafers were damaged beyond repair because of misaligned fingers on the probe card. The vendor should have found this problem before destroying $10,000 worth of wafers. They didn't until the BNL group convinced them of their faulty probe card. This is an example of how closely an ASIC development group must follow the manufacturing process to maintain cost control. Device yields varied greatly, in part because this ASIC was an advanced state-of-the-art technology and the vendor had a poor understanding of the effect of production parameter variations on device performance. This is a situation that is likely to prevail anytime ASIC properties deviate from those of normal production devices. Chip development this far from the mainstream of production chips can only elicit cost plus fixed fee agreements or foundry only vendor responsibility. For the shift register, the final cost was three times the "budgetary" figures initially given. The time from contract signing to delivery of 20,000 working channels was about 36 months.