Future Opportunities for Hadron Spectroscopy at the MPS

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BNL--42241

DE89 008492

December 7, 1988

Paper presented at
The 1988 BNL Workshop on Glueballs, Hybrids and Exotic Hadrons
August 29-September 1, 1988
Brookhaven National Laboratory

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This work was performed under the auspices of the U.S. Department
of Energy under Contract No. DE-AC02-76CH00016.

Revised by 053
MAR 22 1989

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Introduction

Before I go into detailed MPS experiments, I will give a summary of the status of lattice gauge calculations of glueball masses[1] plus glueball and hybrid masses from the bag model[2], and the flux tube model[3].

For the following discussion, I am going to assume that multi-quark states or molecules are best described in terms of the MIT bag model of Jaffe with its spectrum best defined by work done by R.L. Jaffe and F.E. Low using a method called The P-Matrix[4]. Using this method one sees that all 4-quark states will appear as very broad continuum like effects that one would not associate with meson resonances, except for the S^* and the δ which forms a very special threshold $K\bar{K}$ bound systems. There is a possibility that the $E(1420)$ may also be related to the $J^{PC} = 1^{++}$, $qq\bar{q}\bar{q}$ spectrum having its width narrowed by a final state interaction[5].

From the present size lattices it is clear that the ratio of the tensor glueball mass to scalar glueball mass is approximately 1.5. The mass of scalar would be around 1 GeV if one uses the proton mass as calculated in the quenched approximation. Instead of using this proton mass, one uses the string tension from the lattice as a means to determine the scalar mass, one comes up with a mass around 1.4 GeV.

For the bag model, the glueball masses are the $0^{++} = .7$ GeV, the $0^{-+} = 1.4$ GeV, and the $2^{++} = 1.7$ GeV, while for the hybrids it gives the $0^{-+} = 1.2$ GeV, the $1^{-+} = 1.4$ GeV, the $1^{--} = 1.6$ GeV, and the $2^{-+} = 1.8$ GeV. The first excited glueball levels are the $0^{++} = 1.7$ GeV and the $2^{++} = 2.1$ GeV. It turns out that there are candidates for all of the above states. Thus the bag model predicts a very rich spectrum in the mass range of 1.0 - 2.2 GeV.

The flux tube model[3] is based on the strong coupling Hamiltonian of lattice QCD and has the basic scale of the long range confinement string tension. For the flux tube model the glueball masses are the $0^{++} = 1.4$ GeV and the $2^{++} = 2.1$ GeV. The hybrids appear at around 1.9 GeV. It is possible that the extra 0^{-+} around 1.5 [$\iota(1440)$] could be one of these hybrids. If it turns out that the flux tube model is truly the phenomenologically equivalent to the lattice gauge calculations and the many bag model candidates are confirmed, new physics beyond the standard model

This work was performed under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-76CH00016.

will certainly be necessary. An example of just such a possibility was presented by G. Farrar at the BNL workshop[6]. If in SUSY there were light gluinos, the lowest level of gluinoballs will have quantum numbers 0^{-+} and 1^{++} . It is interesting to note that there are two extra states at 1.4 GeV with exactly these quantum numbers.

S-Matrix Approach to $I^G = 0^+$, $J^{PC} = 0^{++}$ and 2^{++} Spectrum

The pion mass being so small, coupled with the conservation of G-parity for the strong interaction has provided the physicist with a model independent determination of the meson spectrum for $I^G = 0^+$ and $J^{PC} = 0^{++}$ and 2^{++} . For pion scattering, the low $|t|$ data is dominated by one pion exchange (OPE). Using The standard OPE extrapolation, one obtains the S-Matrix Argand amplitudes for each of the partial waves. For the following S-Matrix analysis I have used the following processes $\pi\pi \rightarrow \pi\pi$ [7(4)], $\pi\pi \rightarrow K\bar{K}$ [7(4)], $\pi\pi \rightarrow \eta\eta$ [8(6-8)], $\pi\pi \rightarrow \eta\eta'$ [8(7)]. I can also add the reaction $K\bar{K} \rightarrow K\bar{K}$ [10] by assuming that the unnatural exchange for $M = 0$ amplitude for $K^-\bar{p} \rightarrow K\bar{K}\Delta^0$ is pure K-exchange. The channels $J/\psi \rightarrow \gamma\pi^+\pi^-$, $J/\psi \rightarrow \gamma K^+K^-$, $J/\psi \rightarrow \gamma K_S K_S$, $J/\psi \rightarrow \gamma\eta\eta$, $J/\psi \rightarrow \gamma\eta\eta'$ [7(11)] were also fitted because they only have $I^G = 0^+$ and $J^{PC} = 0^{++}$ and 2^{++} below a mass of 2.0 GeV.

In order to describe the J/ψ radiative decay data, I use the generalized Watson theorem of Aitchison [9]. Reference 11 (of Ref. 7) has found that for masses below 2.0 GeV only three meson resonances are necessary to fit all the pseudoscalar-pseudoscalar mass distributions. These three resonances are the $f(1270)$, the $f'(1520)$, and the $\theta(1720)$. The $f(1270)$ and the $f'(1520)$ were confirmed to have a spin of 2 by 5 and 4σ , while the $\theta(1720)$ could be either spin 0 or spin 2. If the $\theta(1710)$ is spin 0 then it could very well be the $S^{*'}(1730)$ [7(13)] resonance. The spin 2 alternative was explored by me in Ref. 7(4). In the light of new data presented at the BNL Workshop[10], one prefers the Breit-Wigner parameters of the $\theta(1710)$ from Ref. 7(4)'s solid curve which are the same as the $S^{*'}$ and the branching fraction $X_a = \Gamma_a/\Gamma_T$ are $X_\pi = .035 \pm .005$, $X_K = .19 \pm .05$, $X_\eta = .05 \pm .04$ and $X_{\text{other}} = .73 \pm .13$.

If I consider the possibility that the $\theta(1710)$ is the $S^{*'}$, I then achieve a fit which is shown in Fig. 9 (of Ref. 7). This fit has four 0^{++} resonances plus a background pole which gives the threshold $\pi\pi$ phase shift (sometimes referred to by nuclear physicists as the σ). These resonances are the $S^{*}(1060)$, the $\epsilon(1266)$ [called the $g_S(1250)$ in Ref. 7(13)], the $\epsilon(1478)$, and the $S^{*'}(1712)$.

Let us consider the two possible mass scale for the above spectrum for the scalars and the tensor states. The bag model gives two scalars and one tensor glueball in the 1.0-2.0 GeV range. The lowest scalar has a mass of around 1.0 GeV. Work by Au, Morgan, and Pennington[11] have shown that there is a

possibility that there is an extra scalar state near 1.0 GeV. The double pole nature of the S^* in their fit may not mean that there are two states, but may mean that the molecular nature of the $qq\bar{q}\bar{q}$ at this threshold cannot be represented by a simple pole using the analytical continuation of the authors below the $K\bar{K}$ threshold. In the bag model the first tensor glueball is around 1.7 GeV and is naturally associated with the spin 2 $\theta(1710)$. The second scalar around 1.5 GeV is easily accommodated as mixing with the $S\bar{S}$ member of the $\ell = 1$ $q\bar{q}$ 0^{++} nonet producing the $\epsilon(1478)$ and the $S^{*'}(1712)$. Reference 12 shows that there is a 0^{++} $\ell = 1$ $q\bar{q}$ nonet which is degenerate with the 2^{++} $\ell = 1$ $q\bar{q}$ nonet. They observed the $\kappa(1430)$ at the same mass as the $K^*(1430)$, plus in my scalar fit I also have detected the $\epsilon(1266)$ which is the scalar counterpart to the $f(1270)$. Reference 10 and Fig. 9a (of Ref. 7) gives the $K\bar{K} \rightarrow K\bar{K}$ spectrum for both 2^{++} and 0^{++} . For the 2^{++} this experiment has probed down to the 20% $K\bar{K}$ coupling level. Because of this lack of sensitivity the $\theta(1710)$ as a spin 2^{++} glueball is still workable. In order to probe at 2% level, one would need a factor of 100 increase in statistics. In Ref. 10 there were 210 events in the $f'(1525)$ peak, I will shortly show that the MPS could achieve 24000 events in the $f'(1520)$ peak. If the $\theta(1720)$ does not show up at that level it would certainly be dead as a 2^{++} .

The flux tube model predicts only one glueball in the mass range 1.0-2.0 GeV. This is a scalar at 1.4 GeV, and is consistent with mixing with the $S\bar{S}$ member of the $\ell = 1$ $q\bar{q}$ 0^{++} nonet and thus producing the $\epsilon(1478)$ and the $S^{*'}(1712)$. This assignment would be favored if the θ turns out to be the $S^{*'}$.

Reference 10 in the spin 2 sector only detects the $f'(1520)$ while in the spin 0 sector they see two very interesting bumps both nearly saturating the unitary limit. The first effect is right at the $K\bar{K}$ threshold and is a very narrow peak of the order of 20 MeV wide. This narrow peak is saturating unitarity. This threshold behavior needs to be explored at a level with a factor of 100 better sensitivity, taking 6 events to 600. From Ref. 10's amplitude analysis, a spin 0 bump occurs right under the $f'(1520)$. The necessity for spin 0 is at the 5σ level, but because of the lack of sensitivity one can not tell if this is the $\epsilon(1477)$ and the $S^{*'}(1710)$ [which one would expect] or a completely different phenomenon.

$$K^-p \rightarrow K_S K_S \Lambda^0(\Sigma^0)$$

On January 24, 1985 the MPS group submitted a Letter of Intent for a AGS proposal in which the reaction $K^-p \rightarrow K_S K_S \Lambda^0(\Sigma^0)$ would be measured using the MESB line operating at 8 GeV/c in a partially separated mode. Operating with a beam rate of around 2×10^6 one would have 40,000 K^- and 40,000 $\bar{p}$ per pulse. With a 2 ft. liquid hydrogen target our intrinsic sensitivity - 80 events per nanobarn in a 1000 hour run. The cross section for $f'(1520)$ going into $K_S K_S$ is around $1.7 \mu\text{b}$ which gives 60,000 visible

$f'(1520)$. A $N \rightarrow N + \geq 2$ gives an acceptance of around 40% thus giving a 24,000 detected $f'(1520)$.

Since we will also have 40,000 $\bar{p}$ going through the MPS, it becomes possible to look at the reactions $\bar{p}p \rightarrow K_S K_S X$ and $\bar{p}p \rightarrow K_S K_S \pi^0$. We expect to obtain of the order of 5000 $f(1270)$ and 1000 $f'(1520)$ from $\bar{p}p \rightarrow K_S K_S X$ and of the order of 500 $f(1270)$ and 100 $f'(1520)$ from $\bar{p}p \rightarrow K_S K_S \pi^0$. One should note that the branching ratio of the $f(1270)$ into $K\bar{K}$ is about 4%, therefore if any new phenomenon is produced at the level of the $f(1270)$ we would also test it down to the 4% level. The $f'(1520)$ is produced at a much smaller level because of the OZI rule. For the exclusive final state $K_S K_S \pi^0$, we will be able to determine the $K\bar{K}$ amplitude ($I = 1$) arising from N - and Δ -exchange and the $K\bar{K}$ amplitude ($I = 0$) from N -exchange. One can easily imagine discovering new states with this type of sensitivity.

Glueball Filters

The topological flow of quark lines from an incoming flavor states to an outgoing flavor states gives one the opportunity to examine reactions where there is complete flavor change. When a break in the topological flavor flow occurs, this break is bridged by a pure gluonic system that must exist for at least a short period of time. Normally the gluonic state is produced by annihilation of a single pair of quarks in a close encounter at short distances thus weak coupling of gluons to quarks leads to the well known OZI rule. For the spin 0 systems there is a well known non-perturbative effect at small distances and is at the core of understanding the $U(1)$ problem for the pseudoscalars.

If one considers $\pi\pi$ scattering which is the lowest threshold meson-meson scattering system and $\phi\phi$ production which is the lowest threshold meson-meson scattering system of complete flavor change, one then has arranged a filter which would select against all ideally mixed systems either suppressing in decay or suppressing in production. The $\pi\pi$ scattering in this filter process restricts one to $J^{PC} = 0^{++}$, 2^{++} , and 4^{++} . Experiment E-747 has found that this spectrum consists of only three 2^{++} resonances[7(1)], Figs. 2-4 (of Ref. 7). The resonances completely break down the OZI suppression and have no accompanying continuum or other J^{PC} states within errors. These states tower (by a factor ~ 50) over the K^+K^- OZI-allowed physical reaction which is mostly a featureless background. They also tower over the $K^+K^-K^+K^-$ reaction by a factor $\sim 1,000$ which appears to be featureless. There is no indication whatsoever of the $h(2030)$ ($1G, J^{PC} = 0^+4^{++}$) which should be strongly produced in π -exchange. The absence of the $h(2030)$ and its SS partner the $h'(2200)$ shows how well the filtering action is working in this channel. These very striking phenomena are very naturally explained in the context of QCD by the production of 1-3 $J^{PC} = 2^{++}$ glueballs.

When a $q\bar{q}$ annihilation occurs at short distances it will couple to a color singlet system of gluons through what is called the U-diagram (Fig. 1). On the other hand when the $\pi\pi$ system annihilates into a tensor glueball it occurs at large distances and couples to a circulating ring of gluons through a diagram called the Crows-foot (Fig. 2). The U-diagram is a pure SU(3) singlet thus giving $4\langle\phi\phi\rangle = 4\langle\omega\omega\rangle = 2\langle K^*K^*\rangle = \langle\rho\rho\rangle$ with $\langle\omega\phi\rangle = 0$. The Crows-foot no longer has the condition that $\langle\omega\phi\rangle = 0$, thus causing a breaking of the SU(3) singlet properties. Flavor mixing caused by glueballs depend on the overlap of the $q\bar{q}$ wave functions with the glueball wave function where annihilation takes place at large distances.

Figure 1

The U-diagram for the decay of a two-gluon glueball into a pair of quarkonium states.

Figure 2

Two Crows-foot diagrams for the decay of a two-gluon glueball into a pair of quarkonium states, where (a) has a different final topology than the U-diagram and (b) has the same.

The widths of glueballs were thought to be narrow because the U-diagram was used to estimate the decay probability. In fact if the glueball could only decay through the U-diagram it would represent a tube of gluonic flux circling the origin with a small probability for annihilation at the origin. However the more likely possibility is for two pairs of quarks to be created in the flux tube where nonperturbative effect are large, thus causing the glueball to break into two pieces.

Another filter exploited for enrichment of glueballs is the radiative decay of the $J/\psi \rightarrow \gamma g g$. In radiative decay of the J/ψ conventional $q\bar{q}$ states such as the n, n' in $J^{PC} = 0^{-+}$ and the f, f' in $J^{PC} = 2^{++}$ plus a general continuum (at least unresolved into resonances) type with the $J^{PC} = 0^{-+}$ are produced. By

looking only at the pseudoscalar-pseudoscalar final states, one filters out the large 0^{-+} amplitude, however in this final states one sees relatively equal production of the f , the f' and the θ . Therefore the J/ψ radiative decay channel clearly cannot be a tight glueball filter or these conventional $q\bar{q}$ objects would not appear in it.

The width of the $J/\psi \rightarrow ggg$ and the branching ratio $J/\psi \rightarrow gg\gamma$ agrees with the perturbative QCD calculations. If the J/ψ radiative decay were strongly coupled to glueballs one might expect that the process $J/\psi \rightarrow \gamma G$ would enhance the radiative decay branching ratio and in the process increase the width of the J/ψ . I think that the small size of the J/ψ leads to a very small overlap with the glueballs and gives rise to the regular U-diagram which goes into the regular $q\bar{q}$ states.

The $\phi\phi$ and Beyond

Are there any other glueballs in this mass region and if so why did E-747 not see them? S. Meshkov [13] has pointed out that in the most simple constituent model of two gluons there will be an exotic glueball with $J^{PC} = 1^{-+}$ near the 2^{++} . However Ref. 2 does not have this state because it depends on longitudinal spin components which can only occur if the gluon has a mass.

The next objective in AGS E-747 is to search for an exotic J^{PC} glueball. However the production mechanism for $|t'| < 0.3$ (which is 95% of our data) is π -exchange (i.e. $\pi^+\pi^-$ annihilation) and thus only $J^{PC} = 0^{++}, 2^{++}, 4^{++} \dots$ etc. can be produced. A- or other exchanges are required to produce an exotic J^{PC} glueball. I have made phenomenological estimates of both π -exchange and A-exchange cross section and conclude that a factor of 8.6 can be gained in A-exchange by lowering the incident momentum to 8.0 GeV/c from the present 22.0 GeV/c; this can be done if we use the MESB and maintain about the same overall acceptance of our apparatus by compacting it. We will also gain an estimated factor of 3.8 in π -exchange rate. I feel that the filtering power of the $\phi\phi$ system makes such a search very worthwhile.

From the above discussion about how glueballs decay, the importance of the Crows-foot diagram leads to the realization the 2^{++} states may decay at some rate into $\omega\phi$. If they are seen in this mode it certainly would be a smoking glueball gun. There is a recently published experiment [14] which claims to have observed a new resonance at around 1.5 GeV that has $J^{PC} = 1^{--}$ and is produced by π -exchange. This state decays by $\phi\pi^0$ which is an OZI-forbidden decay. The upshot is that one needs to detect a ϕ , a π^0 alone or along with a π^+ and a π^- .

At the MPS we have had a lot of experience with K triggers and recently we have constructed TPC modules as part of a heavy ion experiment E-810. K. Foley [15] has discussed the possibility of

using TPC as target region detectors. Using the reaction $\pi^+p \rightarrow \phi\pi^0(\omega)\Delta^{++}$, one could trigger on the production of two K's while also having two particles go into the TPC. This method requires that we pick up the missing π^0 by overall missing mass technique. Reference 12 demonstrated that this technique could be used at 11 GeV/c.

The MPS has run experiments with a lead glass array. One should look at the $\omega\omega$ system because there is evidence from the GAMS spectrometer at IHEP [8] that the θ is being produced around 1.7 GeV plus an other state around 1.95 GeV which could be one of our 2^{++} states.

In Ref. 5 I developed a final state interaction mechanism that may be responsible for the E(1420) meson with $I^G = 0^+$, $J^{PC} = 1^{++}$. I have considered the final state which consists of two K^- mesons and a K^0 . This state has an overall one net unit of strangeness, where the three kaons are in an overall s-wave, therefore a $J^P = 0^-$. We would produce this state using the reaction $K^-p \rightarrow K^-K_S^0K^- \Delta^{++}$. If the final state interaction mechanism that produces the E(1420) is a correct concept, I would expect that a very large threshold enhancement would occur for the three kaon system driven by the successive formation of the δ resonance between the two K^- mesons and the single K^0 . We should be able to make a very good trigger because the final state with two negative kaons are very rare.

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