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# BNL Glueball Review*

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**Abstract**

The glueball session of the BNL workshop on glueballs, hybrids and exotic hadrons is reviewed. This include studies of $K\overline{K}\pi$, $\eta\pi\pi$, $\gamma\rho^{\circ}$, $\pi\pi$, $K\overline{K}$, $\eta\eta$, $\phi\phi$, $\rho\rho$, $\omega\omega$, and $K^*\overline{K}^*$ resonances produced in $\gamma\gamma$, $J/\psi$, $K^-p$ and $\pi^-p$ reactions.

This paper is a condensed summary of the results from the glueball session at the BNL workshop on glueballs, hybrids and exotic hadrons. The results are ordered by topology and efforts are made to make comparisons between different production mechanisms. The discussion begins with a short description of general ideas and models and then proceeds to review the different reactions.

## 1. Introduction to Models

Quantum Chromodynamics with its non–abelian character has the property of multi–gluon interactions which could lead to bound states of pure gluonium.[1] A bound state of two or more gluons, called *glueballs* or *gluonium*, is the subject of an intense search in meson spectroscopy. For two gluons, the symmetry of space-spin-color leads to $J^{pc}$ predictions for different values of angular momentum $\mathbf{L}$ that are shown in Table 1. The underlined values have exotic quantum numbers ( not accessible to $q\overline{q}$ states ) and are called exotics or odd-balls. Since gluons contain no quarks,

| $L$ | $J^{pc}$ | | |
|---|---|---|---|
| 0 | $0^{++}$ | $2^{++}$ | |
| 1 | $0^{-+}$ | $\underline{1}^{-+}$ | $2^{-+}$ |
| 2 | $2^{++}$ | $\overline{0}^{++}$ | $4^{++}$ |
| 3 | $2^{-+}$ | $\underline{3}^{-+}$ | $4^{-+}$ |

Table 1.

Invited talk presented at the meeting of the BNL Workshop on Glueballs, Hybrids and Exotic Hadrons at Brookhaven National Labs, Upton, New York, August 29-September 1, 1988

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gluonium decay into $q\bar{q}$ hadrons and its production in various sources is roughly understood. Gluonium should decay as an SU(3) singlet and they should not have electromagnetic or radiative decays. They are expected to be produced in hard gluon processes such as radiative $J/\Psi$ decays, but they should not be produced or at least be highly suppressed in $\gamma\gamma$ or hadroproduction such as $s\bar{s}$ resonance formation.

The masses of glueballs can be naively estimated by BAG model calculations[2] and rough estimates yield values of 1 GeV for $J^{PC}=0^{++}$, $2^{++}$ for $(TE)^2$ modes, 1.6 GeV for $J^{PC}=0^{++}$, $2^{++}$ for $(TM)^2$ modes, and 1.3 GeV for $J^{PC}=0^{-+}$, $2^{-+}$ for (TE)(TM). Lattice Gauge Models attempt to provide precise mass predictions and several aspects have been reviewed in this conference.[3,4] Recent Monte Carlo calculations are providing consistent results although mass predictions are volume dependent and there is much need for more compute power. In general the theoretical masses have been rising and predictions are hovering around $m(0^{++}) \approx$ 1240-1600 MeV, with ratios of different mesons of $m(2^{++})/m(0^{++}) \approx 1.5$ and $m(0^{-+}) \approx m(2^{-+}) \geq m(2^{++})$.

Other models of gluonium appearing in this conference include flux tube models[5], Bethe–Salpeter egn. models[6], spectral sum rule models[7] as well as the possibility that the glueball width is so large such that it is difficult to verify their existence.[8]

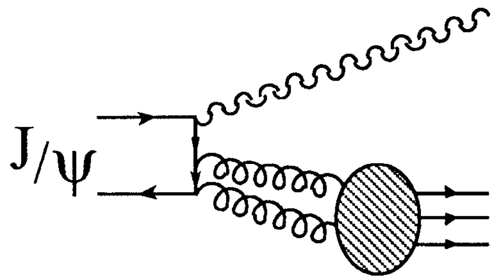


Fig. 1 J/ψ →γgg decays

In general they should look like SU(3) flavor singlets and appear in the 1–2.5 GeV range. The conventional searches for gluonium focus in several areas; (1) extra $0^{-+}$, $0^{++}$, $2^{++}$ resonances in hadroproduction which do not fit into the known $q\bar{q}$ spectrum, (2) gluon enriched channels such as radiative $J/\Psi$ production, (3) OZI violating modes, and (4) double Pomeron exchange in central production.

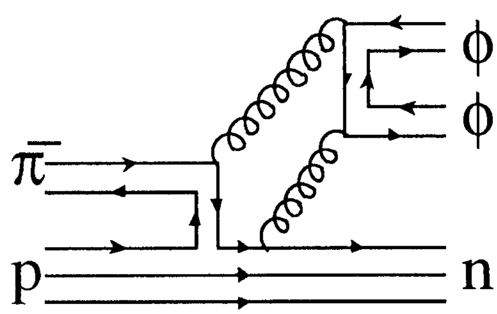


Fig. 2 $\pi^- p \to \phi\phi n$ OZI decays

The radiative $J/\Psi$ decay mechanism is shown in Fig.1. The results from this search come from the Mark III[9-11], DM2[12], Mark II and Crystal Ball groups.

The OZI suppressed decays are shown

in Fig. 2 and results from this study come from the BNL/CCNY group[13]; The central production of gluons is shown in Fig. 3. In this case the process is explained as double pomeron exchange and assuming that the pomeron has gluonic content this could make this process a source of gluonium. The results from central production come from the ITEP,[14] GAMS,[15] WA76[16] and AFS[17] groups. In as much as glueballs can mix with $q\bar{q}$ states, hadroproduction could produce candidates, such as those produced in $\pi^- p \to K\bar{K}\pi+n$ and $\eta\pi\pi+n$. The results of this study come from the BNL/E771,[18,19] BNL/E769[20] and KEK/E135[21] experiments.

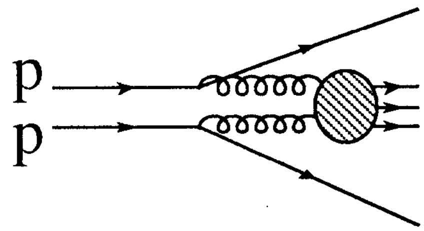


Fig. 3 Central production

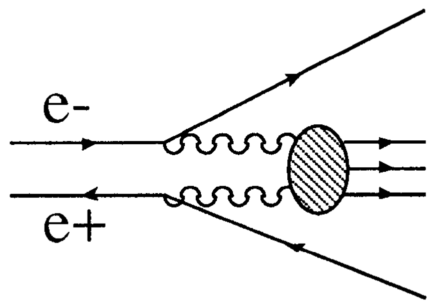


Fig.4 Two photon production

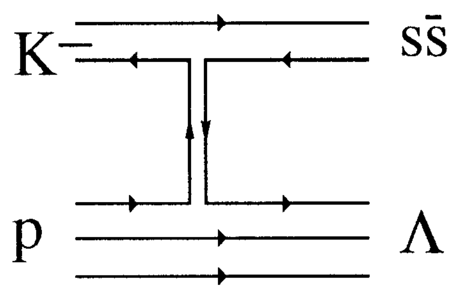


Fig. 5 $K^-p \to s\bar{s} + \Lambda$ production

-We do not expect to find production of glueballs in $\gamma\gamma$, $\gamma\gamma^*$ or in hadronic formation experiments such as K exchange. The $\gamma\gamma$ reaction is shown in Fig. 4 and the K exchange process is shown in Fig. 5. It is important to determine that glueball candidates do not appear in these productions as well as to map out the remaining $q\bar{q}$ states in order to reduce the confusion with glueball states. The $\gamma\gamma$ results come from the TPC,[22,23] Mark II,[24] Crystal Ball[25], ARGUS[26,27] and PETRA ( CELLO, JADE, PLUT0 )[28] groups. The K exchange production is presented by the LASS group.[29,30]

## 2. Study of $0^{-+}$ and $1^{++}$ Resonances

In this topology three body decays that can produce $0^{-+}$ and $1^{++}$ resonances and their production reactions are shown on the right. The main

$$\left\{\begin{matrix} K\bar{K}\pi \\ \eta\pi\pi \\ \gamma\rho^{\circ} \end{matrix}\right\} \begin{matrix} \textit{produced} \\ \textit{from} \end{matrix} \left\{\begin{matrix} \gamma\gamma\ ,\gamma\gamma^{\,*} \\ \pi^- p\,, K^- p\,, pp \\ J/\psi \to \gamma + X \end{matrix}\right\}$$

glueball candidate in these modes is the iota/$\eta(1440)$ seen in radiative $J/\Psi$ decays[31] and in $\pi^- p$ reactions.[32]

In this conference, both the DM2 (L. Stanco)[12] and the Mark III (T. Burnett)[9] have studied $J/\Psi \rightarrow \gamma$+iota/$\eta(1440)$ and performed a spin–parity test of the iota/$\eta(1440) \rightarrow K\bar{K}\pi$. The DM2 groups uses the $K^\circ K^+\pi^-$ and $K^+K^-\pi^\circ$ modes and performs an isobar analysis including the KK* and $\delta\pi$ isobars but not including interference. The DM2 observes a pseudoscalar at 1450 MeV/$c^2$ with roughly equal amounts of $\delta\pi$ and K*K. In addition they observe a evidence for a narrow $1^{++}$ $\delta\pi$ resonance at 1395 MeV/$c^2$ and a shoulder at 1515 MeV/$c^2$ in the non–resonant $K\bar{K}\pi$ channel which could be attributed to the $D'/f_1(1530)$.

The Mark III studies the Dalitz plot distribution using the $K^+K^-\pi^\circ$, $K^\circ K^+\pi^-$ and $K^\circ K^\circ\pi^\circ$ modes and attempted to separate out the $\delta\pi$ and K*K components. Although there is a large $\delta\pi$ channel centered near 1450 MeV/$c^2$, the analysis could not separate the $0^{-+}$ and $1^{++}$ $\delta\pi$ components. The pseudoscalar K*K channel has a large contribution which appears to be at a higher mass than the DM2 results. No $E/f_1(1420)$ is observed, however there is evidence for a non–resonant $K\bar{K}\pi$ signal above 1.5 GeV/$c^2$.

Another result from the Mark III group is a spin–parity test ($1^{++}$ versus $0^{-+}$) of $J/\Psi \rightarrow \gamma\gamma\rho^\circ$ and $\eta\pi^+\pi^-$. In the $\eta\pi^+\pi^-$ mode, there are two prominent peaks at 1.28 and 1.39 GeV/$c^2$. The iota/$\eta(1440)$ is not seen in the mass spectrum. They have been studied with an isobar analysis that includes $\delta\pi$ and $\varepsilon\eta$ with $J^{PC}=0^{-+}$ and $1^{++}$. The lower mass peak favors $1^{++}$ by 3.3$\sigma$ and the upper mass peak favor $0^{-+}$ by 3.8$\sigma$. The lower mass peak can be identified as the $D/f_1(1280)$ and the upper one the $\eta\pi\pi$ signal seen by the KEK group.[21] This spin is contrary to the recent DM2 result discussed in the previous paragraph. In the $\gamma\rho^\circ$ mode, there are again two peaks at 1271±7 and 1432±8 MeV/$c^2$. The lower peak favors $1^{++}$ relative to $0^{-+}$ by 3.9$\sigma$ and the upper peak is not well distinguished between the two spins. The lower peak is identified with the $D/f_1(1280)$ however the resulting radiative width is found to be much larger than expected. If the upper peak is identified with the iota/$\eta(1440)$ the radiative width is $\Gamma(\text{iota}/\eta(1440) \rightarrow \gamma\gamma)=1.2\pm.5$ MeV/$c^2$ which is very large.

A study of $\pi^- p \rightarrow K^\circ K^+\pi^- n$ at 8 Gev from the BNL/E771 experiment (D. Zieminska[18] and S. Blessing[19]) provides evidence for more than one $0^{-+}$ state in the iota/E region. This high statistics experiment studied the t′ dependence and found the $0^{-+}$ wave to be dominant at $0.4 \leq -t' \leq 1.4$ GeV/$c^2$. The $0^{-+}$ $\delta\pi$ and K*K components have different mass distributions indicating the presence of at least two pseudoscalar states; one at 1400 MeV/$c^2$ decaying into $\delta\pi$ and K*K and the other at higher mass decaying into K*K.

The BNL/E769 experiment (N. Cason)[20] has studied the channel, $\pi^- p \rightarrow K^\circ K^\circ \pi^\circ n$ at 21.4 Gev and they observe an iota/$\eta$(1440) like state with t'>.2 GeV. Their Dalitz plot analysis shows evidence for $\delta\pi$ and KK* with $J^{pc}=0^{-+}$ at around 1460 GeV/$c^2$ . They also are able to fit the data with two Breit–Wigner peaks with the lower one consistent with the mass of the E/$f_1$(1420) .

There has been a search by the KEK/E135 experiment (T. Inagaki)[21] in $\pi^- p \rightarrow K^\circ K^+ \pi^- n$ and $\pi^+\pi^-\pi^\circ n$ and $\eta\pi^+\pi^- n$. In the $K^\circ K^+\pi^-$ mode they observe the D/$f_1$(1285) and at 1420 MeV/$c^2$ a $0^{-+}$ resonance decaying into $\delta\pi$ and K*K. New data was taken in the $\eta\pi^+\pi^-$ channel at a slightly higher incident $\pi^-$ momentum and the results are reported to be compatible with previous ones.

The CERN/WA76 experiment (A. Kirk)[16] studies pp $\rightarrow p_f K^\circ K^+\pi^- p_s$ at 300 GeV and observes the D/$f_1$(1280) and the E/$f_1$(1420). The signal at 1420 MeV/$c^2$ is found to be $J^{pc}=1^{++}$ and mostly K*K.

The SLAC/LASS experiment (B. Ratcliff[30] and D. Aston[29]) studies $K^- p \rightarrow K^\circ K^+\pi^- \Lambda$ at 11 GeV and they observe a sharp rise in the K*K channel and a peak at 1.5 GeV/$c^2$. The partial wave analysis determined this signal to be $1^+$ K*K and this is attributed to the D′(1530) which could be the $s\bar{s}$ isoscalar $1^{++}$ partner to the D/$f_1$(1280) instead of the E/$f_1$(1420). Neither the E/$f_1$(1420) nor the iota/$\eta$(1440) is seen.

The evidence for the $\gamma\gamma^* \rightarrow$E/$f_1$(1420)$\rightarrow K^\circ K^+\pi^-$ in the TPC, Mark II, CELLO and JADE groups was discussed (D. Caldwell[23], M. Feindt[28], G. Gidal[24]). The mixing angles extracted from the $\gamma\gamma^*$ partial widths of the D/$f_1$(1280) and the E/$f_1$(1420) do not agree with ideal mixing or the Gell–Mann–Okubo mass formula. The partial widths are model dependent on the form factor and may affect the final values. The $\gamma\gamma^* \rightarrow \eta\pi\pi$ channel has also been investigated and a clear D/$f_1$(1280) is seen but neither the E/$f_1$(1420) nor D′(1530) is seen.

The ASTERIX experiment[33] at LEAR studied $p\bar{p}$ annihilations at rest in the reaction, $p\bar{p} \rightarrow K^\circ K\pi\ \pi\pi$, and observed two peaks at the D/$f_1$(1280) and E–iota regions. By comparing the production rates on a gaseous or liquid targets they determined it is produced only from S wave $p\bar{p}$ and conclude it is pseudoscalar.

The summary of the masses of the resonances in the iota/$\eta$(1440)–E/$f_1$(1420) region are listed in table 2. Both the E/$f_1$(1420) and the iota/$\eta$(1440) are extra states not predicted by the quark model for the $0^{-+}$ and $1^{++}$ nonets assuming the D′(1530)

is the correct $1^{++}$ $s\bar{s}$ isoscalar. The DM2 and Mark III results are similar observing a pseudoscalar and evidence that the iota/$\eta(1440)$ is more than a single resonance. The iota/$\eta(1440)$ in hadronic production from BNL and KEK has similar results with mounting evidence that the iota/$\eta(1440)$ is more than a single resonance. The quasi–two body decay appears in roughly equal amounts of $\delta\pi$ and K*K although there appears to be no $\eta\pi\pi$ decays seen in J/$\Psi$ decays. There are models[34] that explain the iota/$\eta(1440)$ as a $K\bar{K}$ molecule and solve the puzzle of no $\eta\pi\pi$ but $\delta\pi$ in the $K\bar{K}\pi$ mode of the iota/$\eta(1440)$.

| Group | Mode | mass | spin |
|---|---|---|---|
| DM2 | $J/\psi\to\gamma KK\pi$ | ≈1450 | $0^{-+}$ |
| Mark III | $J/\psi\to\gamma KK\pi$ | 1447±9 | $0^{-+}$ |
| E769 | $\pi^-p\to K^\circ K^+\pi^-n$ | 1453±7 | $0^{-+}$ |
| E771 | $\pi^-p\to K^\circ K^\circ\pi^\circ n$ | 1419±1 | $0^{-+}$ |
| E135 | $\pi^-p\to K^\circ K^+\pi^-n$ | 1424 | $0^{-+}$ |
| LASS | $K^-p\to K^\circ K^+\pi^-\Lambda$ | 1530 | $1^{++}$ |
| TPC,MKII | $\gamma\gamma\to K^\circ K^+\pi^-$ | 1433 | $1^{++}$ |
| WA76 | $pp\to K^\circ K^+\pi^-pp$ | 1431±2 | $1^{++}$ |
| ASTERIX | $p\bar{p}\to K^\circ K\pi\pi\pi$ | 1413±8 | $0^{-+}$ |

Table 2.

The E/$f_1(1420)$ is seen in $\gamma\gamma^*$ and central production and not in radiative J/$\Psi$ decays. The E/$f_1(1420)$ has been explained as a hybrid states with an exotic $J^{PC}=1^{-+}$. The angular distributions from $\gamma\gamma^*$ production are closer to $1^{++}$ but do not rule out $1^{-+}$.

## 3. Study of $0^{++}$ and $2^{++}$ Resonances

In this mode two pseudoscalars resonances are produced in the following reactions shown on the right. The study of scalar and tensor resonances has focused on evidence for the theta seen in J/$\Psi \to \gamma\theta(1700)$, $\theta \to$ KK, $\pi\pi$, and $\eta\eta$ and the G(1590) seen in $\eta\eta$, $\eta\eta'$ and $4\pi^\circ$.

$$\left\{\begin{matrix} K\bar{K} \\ \pi\pi \\ \eta\eta \end{matrix}\right\} \begin{matrix} produced \\ from \end{matrix} \left\{\begin{matrix} \gamma\gamma \\ \pi^- p, K^- p, pp \\ J/\psi \to \gamma \quad + X \end{matrix}\right\}$$

The Mark III group (D. Hitlin)[10] has studied radiative J/$\Psi$ decays to $K\bar{K}$ and presented preliminary results using the full statistics. In the $\theta$ region if all events are assumed spin 2 or all spin 0, then spin 2 is preferred in the $K_SK_S$ mode which is background free but in the charged $K^+K^-$ mode, spin 0 is slightly preferred with some background from KK* and $\rho\pi$. The analysis does not rule out a combination of spin 2 and spin 0, such as the S*(1700) candidate.[35]

One of the problems of the $\theta$ is the non–flavor symmetry of its decay. The rate of the $\theta$ into $K\bar{K}/\eta\eta/\pi\pi$=1.0/0.27/0.29 whereas they should all be 1.0/0.17/2.0 . A possible solution to this problem has been suggested that the decay should have a soft form factor.[36] With the appropriate exponential factor, the prediction becomes 1.0/0.29/0.32 which is very close to what is observed. A similar idea[37] has been previously proposed to explain the anomalous $\Psi'$ and $J/\Psi$ and $\phi$ decays to $\rho\pi$.

Another glueball candidate is the G(1590) from the GAMS group (F. Binon).[15] They observe this scalar in $\pi^- p$ production in the $\eta\eta$, $\eta\eta'$ and $4\pi^\circ$ channels. This has been seen with incident pions energies of 38, 100 and 230 GeV/$c^2$. Also more recently it has been seen in $\pi^- N \rightarrow$ G(1590) $N\pi^-$, G(1590)$\rightarrow\eta\eta$ at small longitudinal momentum ($X_f \approx 0$). This particular reaction is expected to enhance glueball production via double Pomeron exchange.[38]

The ITEP group (Sokolovskiy)[14] has studied $\pi^- p \rightarrow K^\circ K^\circ n$ and $K^- p \rightarrow K^\circ K^\circ Y^*$ at 40 GeV/$c^2$. In the $K^- p$ channel, only the f′(1520) is observed. In the $\pi^- p$ channel there is possible evidence for the S*(1720), $\varepsilon$(1440),$\theta$(1700) as a interference dip, the f(1980) and the $\xi$(2.2). No G(1590) was seen.

The LASS group[29] has studied the $K\bar{K}$ decays and they do not see the $\theta/f_2(1720)$ but they only see the $f'/f_2(1520)$ and have evidence for a scalar underneath the $f'/f_2(1520)$), a structure at 1850 MeV/$c^2$ and a high mass spin 4 resonance at 2210 MeV/$c^2$ which may be the $\xi$(2.2) seen by the Mark III group[39].

The WA76 group[16] has studied the $\pi^+\pi^-$, $K^+K^-$ and $K_SK_S$ modes in their central production. In the $\pi^+\pi^-$ mode they observe a shoulder attributed to the S*. In the $K\bar{K}$ modes they observe two peaks consistent with the $\theta/f_2(1720)$ and the $f'/f_2(1520)$. They have not yet performed a spin–parity test on these two peaks.

A study (M. Pennington)[17] of the high statistics AFS data has provided evidence for a two scalar resonance nearly degenerate at the S* mass. The analysis fits all the high statistics data on $\pi\pi\rightarrow\pi\pi(K\bar{K})$ and $pp\rightarrow pp\pi\pi(K\bar{K})$ with $0^{++}$ partial waves using amplitudes with coupled channel unitarity. The data can be fit with two narrow resonances, the lower mass object is attributed to the conventional S* and the higher one from the scalar glueball.

The Mark III group (U. Mallik)[11] has searched in radiative decays, $J/\Psi\rightarrow\gamma\pi^+\pi^-$, for the scalar glueball decaying into $\pi^+\pi^-$ and they have set upper limits for a narrow width resonance over the mass range and a broad resonance under the $\rho^\circ$ and below the $f_2(1270)$. They have observed scalar production in $J/\Psi\rightarrow\gamma\pi^+\pi^-$ and $J/\Psi\rightarrow\gamma K^+K^-$ production near threshold.

The tensor and scalar results are shown in table 3. The list is getting very large indeed. In addition to its radiative J/Ψ production, the case for the θ/$f_2$(1720) to be a glueball candidate is strenghtened if it is found in central production by the WA76 group. If there is a scalar lurking underneath the f′/$f_2$(1520) as claimed by the LASS group it would be very difficult to extract out of the J/Ψ data and verify. If there is a S*(1720) in the J/Ψ data it would be very unexpected because the S* itself has not be detected and upper limits have been set in radiative J/Ψ decay.

| Group | Mode | Mass | Spin |
|---|---|---|---|
| ITEP | $\pi^- p \to K\bar{K}n$ | S*(1720) | $0^{++}$ |
| | | θ(1700) | $2^{++}$ |
| | | ξ(2.2) | $2^{++}$ |
| LASS | $K^- p \to K\bar{K}\Lambda$ | X(2.2) | $4^{++}$ |
| | | X(1.525) | $0^{++}$ |
| WA76 | $pp \to K\bar{K}pp$ | X(1720) | ? |
| GAMS | $\pi^- p \to \eta\eta n$ | G(1590) | $0^{++}$ |
| AFS | $pp \to \pi\pi pp$ | X(993) | $0^{++}$ |
| | | X(988) | $0^{++}$ |
| MK3,DM2 | $J/\psi \to \gamma K\bar{K}$ | θ(1700) | $2^{++}$ |
| MK3 | $J/\psi \to \gamma K\bar{K},\pi\pi$ | threshold | $0^{++}$ |

Table 3.

The "split" S* signal suggested by the AFS data is very intriguing. Recently the E691 tagged photon experiment has seen the decay $D_s \to S^*\pi$, where the $D_s$ is the charm–strange pseudoscalar. If the signal they observe is the real $s\bar{s}$ isoscalar $0^{++}$, then the question is where is the other scalar. An interesting check would be to see if the S* seen in $J/\Psi \to \phi S^*$ is the very same seen in E691. If they are different then, this could give rise to new evidence for a scalar glueball near 1 GeV/$c^2$.

**4. Study of Vector–Vector Resonances**

Pairs of vector resonances have been observed in the following reactions shown on the right. In the well known OZI violating mode, $\pi^- p \to \phi\phi n$ at 22 GeV, a resonance called the $G_t$, has been presented several years ago by the BNL/CCNY group.[13] This high statistics study had a very complete partial wave analysis that fit the data with three K-matrix poles, all $J^{PC}=2^{++}$, with masses near threshold at 2 GeV.

$$\left\{\begin{matrix}\phi\phi\\ \rho\rho\\ \omega\omega\\ K^*K^*\end{matrix}\right\}\ \begin{matrix}\textit{produced}\\ \textit{from}\end{matrix}\ \left\{\begin{matrix}\gamma\gamma\\ \pi^- p\\ J/\psi \to \gamma + X\end{matrix}\right\}$$

From the DM2 and Mark III groups[11,12] evidence has been presented for $J/\Psi \to \gamma$+vector–vector decays with threshold structures all with $J^{PC}=0^{-+}$. The vector-vector modes include $\rho^\circ\rho^\circ$, $\rho^+\rho^-$, $\omega\omega$, $\phi\phi$ and in addition a new mode into

$K^{\circ *}\overline{K}^{\circ *}$ has been observed. There has also been a search for the $\omega\phi$ mode but it was not found. These structures all appear near threshold. They have been determined to be pseudoscalar resonances by a study of the $\chi$ angular distribution.[40] They have been interpreted as a large multichannel resonance along with the iota/$\eta$(1440).[41] Upper limits for the $G_t$ in $\phi\phi$($<1.24\times10^{-4}$) and in $\rho^\circ\rho^\circ$ ($<0.9\times10^{-4}$) have been set and the latter limit contradicts a model[42] developed to explain the $G_t$ as a glueball with radiative J/$\Psi$ production.

Vector–vector structures are also seen in two photon production as shown from the ARGUS[26,27] and TPC[22] groups. The $\rho^\circ\rho^\circ$, $\rho^+\rho^-$, $\omega\omega$, $K^{*\circ}\overline{K}^{*\circ}$, and $K^{*+}K^{*-}$ modes have been seen but not the $\phi\phi$, $\omega\phi$ or $\rho\phi$ modes. Also the $\rho^+\rho^-$ has been found to be suppressed relative to the $\rho^\circ\rho^\circ$ which indicates that they are not isoscalar. These analyses are performing spin–parity tests and there is evidence for $J^P=2^+$ dominance.

Great excitement occurred when the $q^2\overline{q}^2$ models[43,44] were able to explain the $\rho^\circ\rho^\circ$ enhancements and the $\rho^+\rho^-$ suppression as the production of isotensor $2^{++}$ states. In these models each of the two photons pair to produce a $q\overline{q}$ pair which provide a source of 4 quarks. The $q^2\overline{q}^2$ models, however made further predictions for production of $\omega\phi$ and these were not found which may be a serious problem for the models. These models[43] have a natural extension to radiative J/$\Psi$ decays and the $G_t$. In this case the two photons are replaced by two gluons which produce the $q\overline{q}$ pairs. The $G_t$ is tensor and would be naturally classified as a $s^2\overline{s}^2$ states. The vector–vector pairs in radiative J/$\Psi$ decays however are pseudoscalar so this model may not apply here. The vector–vector states are listed in table 4. They all have masses near threshold.

| Group | Mode | Spin |
|---|---|---|
| BNL/CCNY | $\pi^- p \to \phi\phi n$ | $2^{++}$ |
| DM2,MK3 | $J/\psi \to \gamma + \phi\phi$ | $0^{-+}$ |
| | $K^*K^*$,$\omega\omega$ | $0^{-+}$ |
| | $\rho^\circ\rho^\circ$,$\rho^+\rho^-$ | $0^{-+}$ |
| TASSO,PLUTO | $\gamma\gamma \to \rho^\circ\rho^\circ$, | $2^{++}$ |
| CELLO,ARGUS | $\rho^+\rho^-$,$\omega\omega$,$K^{*\circ}K^{*\circ}$, | |
| TPC ,JADE | $K^{*+}K^{*-}$ | |

Table 4.

## 5. Summary

In this summary the striking feature of the data is the OZI nature of the reactions and their discrepancy between production and decay. Most of the unusual states appear to decay into strange states, iota/$\eta$(1440)$\to K\overline{K}\pi$, E/$f_1$(1420)$\to K\overline{K}\pi$, $\theta$/$f_2$(1720)

$\rightarrow K\bar{K}$, and $G_t \rightarrow \phi\phi$, yet the production is non–strange, $J/\Psi \rightarrow \gamma + X$, $\gamma\gamma^*$, pp, $p\bar{p}$, and $\pi^- p$. In constrast when these states are searched for in $s\bar{s}$ production in $K^- p$, they are not found. This is ample evidence for a non–$q\bar{q}$ production process which lends strong support for the creation of a gluonium type of resonance.

The attempt to precisely verify the existence of pure gluonium states is somewhat lacking guidance due to the early stage of the theoretical models. So far the candidates we have in our hands right now are not yet fully understood. The masses from Lattice Gauge Theories are changing and rising. Also there are no well accepted predictions for the width and only rules of thumb. Unfortunately smoking gun tests such as the discovery of the chi states for charmonium have not been made for gluonium. Partly, this is because of the the models are still evolving and also because of the experimental complexity in hadron spectroscopy in the 1–2.5 GeV/$c^2$ mass region. This complexity provides the need for high statistics and careful spin–parity tests as done by the E771, BNL/CCNY and LASS groups.

All of these combined studies from $J/\Psi$ decays, hadron production and $\gamma\gamma$ production provide a remarkable verification of the $q\bar{q}$ model. This reinforcement of our understanding of the conventional $q\bar{q}$ spectrum gives us confidence to believe that the unusual states are really unusual and worth the effort to pursue experimentally and theoretically.

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