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Summary of Hadron95

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abstract

This is a written version of the talk I gave at the end of the Conference. It contains certain 'filtered' highlights with some additional—and relevant—material not presented at the Conference. In his summary (Part I) of the conference, M. Pennington covers the theoretical issues brought up at the meetings and the experimental information regarding the $J^{PC} = 0^{++}$ and 2^{++} glueball candidates and, more generally, the states belonging to natural spin-parity series.

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1 Introduction

This review covers the states belonging to the unnatural spin-parity series, *i.e.* $J^{PC} = 0^{-+}, 1^{++}, 2^{-+}$, and, in addition, the exotic quarkonia with $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$. M. Pennington reviews, in Part I of the Summary of Hadron95, the theoretical progress made so far in our attempt to understand non-perturbative QCD. In addition, he reports on the current status of the natural-parity states, which includes the scalar and the tensor glueball candidates. However, certain natural-parity states, not covered by M. Pennington in his summary, are briefly commented upon in this review.

Many important and significant results have been presented at this conference; every speaker knows the importance of his or her own talk. I believe, however, that a litany of a series of talks given at the conference may not be very helpful as a summary. For that the reader may thumb through the pages of the Proceedings. Instead, I have culled some of the new results presented and put together several coherent pictures—on a few selected topics.

In Section 2, some recent results on the heavy-quark systems are given. In particular, a short comment is made on the discovery of the top quark. Section 3 is devoted to a discussion on the current status of the unnatural-parity states seen in the E/ι region. The reader will note that I brought together new as well as some old results in this review. The current status of the exotic meson searches is dealt with in Section 4. Several other noteworthy results presented at the conference are given in section 5. Finally, conclusions and future prospects are given in Section 6.

2 Some recent results on heavy-quark spectroscopy

One major advance in this field is certainly the discovery of the top quark. Both CDF and D0 at Fermilab Tevatron find evidence of the $t\bar{t}$ production. S. Leone [1] presented the CDF results at the Conference; the top-quark mass is

$$M_t = 180 \pm 12 \begin{array}{l} +\,19 \\ -\,15 \end{array} \quad \text{GeV} \tag{1}$$

The statistical significance [2] for this data is 4.8σ. The D0 collaboration determined the top mass [3] to be

$$M_t = 199 \pm 20 \pm 20 \quad \text{GeV} \tag{2}$$

The quoted statistical significance is 4.6σ.

Another noteworthy result comes from the LEP experiments, reported by M. Feindt [4] at this conference. Using either the 'rapidity algorithm' or the vertex separation method, they are now able to isolate b-jets with high purity. One can therefore study excited B mesons decaying into $B+\gamma$, $B^{(*)}+\pi$ and excited B_s mesons decaying into $B^{(*)}+K$, where the γ's, π's and K's come from the main interaction vertex and are outside the $B^{(*)}$ decay. They find $M(B^*) - M(B) = 45.7 \pm 0.4$ MeV from the decay $B^* \to B\gamma$ and $M(B^{**}) = 5730 \pm 9$ MeV from the decay $B^{**} \to B\pi$ (these are LEP averages). From a study of the decay $B_s^{**} \to BK$, OPAL obtains $M(B_s^{**}) = 5884 \pm 15$ MeV with $\Gamma(B_s^{**}) = 47 \pm 22$ MeV, while preliminary DELPHI results indicate $M(B_{s1}) = 5888 \pm 4 \pm 8$ MeV with $\Gamma(B_{s1}) < 60$ MeV and $M(B_{s2}^*) = 5914 \pm 4 \pm 8$ MeV with $\Gamma(B_{s2}^*) < 50$ MeV. Employing the same technique on the Λ_b-enriched sample (by identifying a proton or a Λ decay among the decay products), DELPHI found first evidence of the decay $\Sigma_b \to \Lambda_b + \pi$. The results are $Q(\Sigma_b) = 33 \pm 3 \pm 5$ MeV and $Q(\Sigma_b^*) = 89 \pm 3 \pm 5$ MeV. Thus, one is beginning to see heavy-quark spectroscopy which involves jets in the decay channels.

3 E/ι saga

Five new results on the E/ι mesons have been presented at this conference. In addition, F. Nichitiu gave a review of the whole subject.[5] A concise summary of the new (as well as some old) results is given in Table 1.

Instead of simply reporting on the results, I will try to show how different production mechanism excite different components of the E/ι meson: in the $\eta\pi\pi$ and $K\bar{K}\pi$ mass spectra above 1.35 GeV, there exist four states, one $J^{PC} = 1^{++}$ state, two $J^{PC} = 0^{-+}$ states and one $J^{PC} = 1^{+-}$ state, *i.e.* $f_1(1440)$, $\eta(1400)$, $\eta(1460)$ and $h_1(1400)$. I will start with the production processes which seem to excite only one component of the E/ι and then progress toward those final states exhibiting more than one component and finally end with a discussion on the reaction which seems to excite all four.

G. Gutierrez [6] presented at this Conference observation of a single $J^{PC} = 1^{++}$ state in the $K\bar{K}\pi$ system, produced centrally in pp interactions at 800 GeV/c at Fermilab. It is known phenomenologically that the states having the quantum numbers $J^{PC} = 0^{++}$, 1^{++} and 2^{++} are produced predominantly in the central region. One may note that the S-wave fusion of two tensor glueballs (corresponding to the Pomeron trajectory) of unequal imaginary mass would produce the states with $J^{PC} = 0^{++}$, 1^{++}, 2^{++}, 3^{++} and 4^{++}. It is therefore not surprising that the $f_1(1420)$ should be produced in the central region. Similarly, Armstrong *et al.*[7] found that a single $f_1(1420)$ is produced in the central region from the π^+p and pp interactions at 85 and 300 GeV/c at CERN Omega Spectrometer.

C. Amsler [9] of the Crystal Barrel Collaboration presented at this Conference evidence of one $J^{PC} = 0^{-+}$ $\eta\pi\pi$ state at the same mass, produced in the reaction $\bar{p}p(\text{at rest}) \to \eta\pi\pi + \pi\pi$. One recalls that Baillion *et al.* saw a single 0^{-+} state at the same mass [8] in exactly the same reaction.[a] Why should a 0^{-+} state be produced in this reaction? For the answer one must first note that an isoscalar $\bar{p}p(\text{at rest})$ has the quantum numbers $J^{PC} = 0^{-+}$ and $G = +1$. One the other hand, the low-mass $\pi\pi$ recoil system must have the quantum numbers $I = 0$, $J^{PC} = 0^{++}$ and $G = +1$. If one now assumes that the $\eta\pi\pi$ system is produced in a relative S wave against the $\pi\pi$ recoil system, then the only allowed quantum numbers for the $\eta\pi\pi$ system are in fact $I = 0$, $J^{PC} = 0^{-+}$ and $G = +1$.

The Obelix Collaboration studied the E/ι region in the same reaction as that of the Crystal Barrel experiment but in the decay channel $K\bar{K}\pi$. One may expect that the $I = 0$, $J^{PC} = 0^{-+}$ states should again dominate the system—indeed this is what the collaboration found, see P. Temnikov.[10] However, they found two 0^{-+} states, one near 1400 MeV coupling to $K\bar{K}\pi$ and the other at 1460 MeV coupling to $K^*(890)\bar{K}$. If the second state is assumed to couple only to a $K^*(890)$ intermediate state, then it cannot couple to $\eta\pi\pi$; this may explain absence of this state in the Crystal Barrel data cited in the previous paragraph.

[a] This is in fact the very first observation of the E/ι state, which they named the E. Consequently, the 'correct name' for this 0^{-+} state should in fact be the $E(1420)$.

In a study of the $K\bar{K}\pi$ system produced in the J/ψ radiative decays, the Mark III collaboration [11] found all three: one $J^{PC} = 1^{++}$ state and two $J^{PC} = 0^{-+}$ states. The same conclusion was reached by the DM2 collaboration [12] in the same decay channel.[b] Evidently, all three must have high gluon content, as the production processes—the central region in the pp annihilations at rest and the J/ψ radiative decays—are thought to be rich in gluons. At this conference, Huang [13] gave a talk representing the BES group on the J/ψ radiative decays: $J/\psi \to K\bar{K}\pi + \gamma$ and $J/\psi \to \eta\pi^+\pi^- + \gamma$. From a moment analysis of the $K\bar{K}\pi$ system, they conclude one $J^{PC} = 0^{-+}$ and two $J^{PC} = 1^{++}$ states. Thus, one is confronted with the results of an analysis, which seem to be at variance with all the other data being reviewed here. However, one must be cautious with the technique of the moment analysis; it may not be as sensitive as a full isobar analysis, which has been applied to all the other data.

Finally one may cite the results of an MPS experiment [14] at BNL. The E771 collaboration studied the $K\bar{K}\pi$ system produced in π^-p interactions at 8 GeV/c. One should note that, although the production reaction is the classic channel for detecting conventional quarkonia, there is one important difference—in that the decay modes under investigation are not those of quarkonia belonging to the leading Regge trajectories. It follows therefore that the gluonic hadrons should be observed in the $K\bar{K}\pi$ system. As a matter of fact, they not only see all three states, commented upon in previous paragraphs but also a $J^{PC} = 1^{+-}$ state in the E/ι region. That this state is mostly an $s\bar{s}$ resonance is borne out by the the fact that it is the most prominent in the $K\bar{K}\pi$ system produced in the K^-p interactions [15] at 8 GeV/c. (This state was previously seen by LASS.[17]) It may be worth emphasizing that the π^-p reactions at intermediate energies seem to be the least restrictive of the quantum numbers for the produced resonances: one observes all four, *i.e.* one $J^{PC} = 1^{++}$ state, two $J^{PC} = 0^{-+}$ states and one $J^{PC} = 1^{+-}$ state. However, the decay channels play an important role. Indeed, in a partial-wave analysis of the $\eta\pi\pi$ system from the reaction $\pi^-p \to \eta\pi^0\pi^0 n$ at 100 GeV/c, the GAMS group [28] finds mainly the $J^{PC} = 0^{-+}$ states in the E/ι region, presumably due to absence of the $K^*(890)$ intermediate state. In addition, another MPS collaboration E747 [29] studied the reaction $\pi^-p \to K_SK_S\pi^0 n$ at 21.4 GeV/c; the statistics were limited, but the data on $K_SK_S\pi^0$ system are compatible with two $J^{PC} = 0^{-+}$ states.

In Table 1 is given a summary of the masses and widths of various states observed in the E/ι region. Because of the differences in the algorithm used to determine the mass and width, it would not make very much sense to combine the various results for averages; in particular, two $J^{PC} = 0^{-+}$ states are so close that one should use unitarized form of Breit-Wigner functions to determine the masses and the widths.

4 J^{PC}-exotic meson searches

The mesons belonging to the series $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$ and $J^{PC} = 0^{--}$ cannot be $q\bar{q}$ states; therefore they are either $q\bar{q} + q\bar{q}$ or $q\bar{q} + g$. There exist two $J^{PC} = 1^{-+}$ exotic meson candidates, an $\eta\pi$ state at 1.3–1.4 GeV in P-wave and a $f_1(1285)\pi$ at 1.9–2.0 GeV in S-wave.

The $\eta\pi$ P-wave state was seen originally by GAMS [18] in the reaction $\pi^-p \to \eta\pi^0 n$ at

[b]They have used the isobar model in their analysis, but they have neglected possible interference effects between the waves of same spin-parity.

Table 1: Masses and widths of various states observed in the E/ι region

J^{PC}	M(MeV)	Γ(MeV)	isobar[a]	reference
1^{++}	1432 ± 5	63 ± 15	$K^*(890)$	MPS [16]
1^{++}	$1443 {}^{+7}_{-6} {}^{+3}_{-2}$	$68 {}^{+29}_{-18} {}^{+8}_{-9}$	$K^*(890)$	MkIII [11]
1^{++}	1430 ± 4	58 ± 10	$K^*(890)$	Omega [7]
1^{++}	1435 ± 3	59 ± 5		BES [13]
1^{++}	1497 ± 2	44 ± 7		BES [13]
1^{++}	1462 ± 20	129 ± 41	$K^*(890)$	DM2 [12]
0^{-+}	1407 ± 3	75 ± 6	$a_0(980)$	MPS [16]
0^{-+}	$1416 \pm 8 {}^{+7}_{-5}$	$54 {}^{+37}_{-21} {}^{+13}_{-24}$	$a_0(980)$	MkIII [11]
0^{-+}	1409 ± 3	86 ± 10	$a_0(980)$	CB [9]
0^{-+}	1415 ± 2	59 ± 4	none	Obelix [10]
0^{-+}	1467 ± 3	89 ± 6		BES [13]
0^{-+}	1459 ± 5	75 ± 9	$a_0(980)$	DM2 [12]
0^{-+}	1412 ± 5	27 ± 9	$a_0(980)$	MPS [29]
0^{-+}	1405 ± 10	135 ± 21	$K^*(890)$	MPS [16]
0^{-+}	$1490 {}^{+14}_{-8} {}^{+3}_{-16}$	$91 {}^{+67}_{-31} {}^{+15}_{-38}$	$K^*(890)$	MkIII [11]
0^{-+}	1460 ± 10	100 ± 10	$K^*(890)$	Obelix [10]
0^{-+}	1421 ± 14	63 ± 18	$K^*(890)$	DM2 [12]
0^{-+}	1477 ± 6	66 ± 22	$K^*(890)$	MPS [29]
1^{+-}	$1344 {}^{+29}_{-43}$	$40 {}^{+38}_{-40}$	$K^*(890)$	MPS [15]
1^{+-}	1380 ± 20	80 ± 30	$K^*(890)$	LASS [17]

[a] The notation 'none' means that there are no isobars and a direct 3-body decay dominates. Blank space signifies that the analysis method is independent of isobars.

100 GeV/c, and later by KEK [19] in the reaction $\pi^- p \to \eta\pi^- p$ at 6.3 GeV/c. But they differ in mass (some 80 MeV) and are produced via different exchanges, implying two different couplings for this state, *i.e.* either to $b_1(1235)\pi$ or to $\rho\pi$ but not to both. It is clear that a new initiative is required to examine the $\eta\pi$ system. BNL E852 aims to do just that, with the reactions $\pi^- p \to \eta\pi^0 n$ and $\pi^- p \to \eta\pi^- p$ at 18 GeV/c. Preliminary results on this data have been presented by Cason.[20] The asymmetries are significant in the mass region 1.3–1.5 GeV for both the $\eta\pi^0$ and $\eta\pi^-$ Jackson-angle distributions, but their magnitudes are small compared to the KEK data. In addition, the asymmetries exhibit different mass dependence, indicating different admixture of natural and unnatural exchanges. The combined E852 data from 1994 and 1995 runs should be about a factor of ten more than the published data of KEK and GAMS. The VES collaboration [21] investigated the decays $X^- \to \eta\pi^-$ and $X^- \to \eta'\pi^-$ in the reaction $\pi^- N \to X^- N$ at 37 GeV/c. They observe no significant $J^{PC} = 1^{-+}$ $\eta\pi^-$ wave in the mass region 1.2–1.6 GeV; instead, they report a broad 400 MeV wide object in the $\eta'\pi^-$ spectrum centered at 1.5 GeV.

An earlier BNL E818 collaboration [22] studied the reaction $\pi^- p \to f_1(1285)\pi^- p$ at 18 GeV/c, with $f_1(1285) \to K\bar{K}\pi$, and found a resonant $J^{PC} = 1^{-+}$ wave at mass 1.9–2.0 GeV. The statistics were limited; however, the current E852 collaboration [23] have amassed some 100 times the E818 statistics in the same reaction, with $f_1(1285) \to \eta\pi\pi$. The E852 collaboration hopes to run again in 1997 with a low-mass segmented Cerenkov counter to identify charged K's; this will give a large-statistics sample for the same reaction, but in the decay channel $f_1(1285) \to K\bar{K}\pi$.

According to the KEK results,[19] a $J^{PC} = 1^{-+}$ $\eta\pi^-$ system is produced by unnatural-parity exchange, indicating that the state may have a substantial coupling to $\rho^0\pi^-$. If so, the exotic state could also decay into $\rho^0\pi^-$ and $\rho^0 \to \pi^+\pi^-$ as the main decay mode.[c] The BNL E852 collaboration has embarked on a high-statistics study of the $\pi^+\pi^-\pi^-$ system in the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c. Preliminary results [24] show that the $J^{PC} = 1^{-+}$ wave is small but could be statistically non-negligible. One firm conclusion at this point is that the ratio of this exotic wave to the $J^{PC} = 2^{++}$ $a_2(1320)$ signal is smaller than that given previously be the VES collaboration [21] in the reaction $\pi^- N \to \pi^+\pi^-\pi^- N$ at 37 GeV/c.

The GAMS collaboration [25] reported on the observation of a narrow (width less than 50 MeV) at mass 1662 ± 7 MeV in the $\omega\eta$ system, from a study of the reaction $\pi^- p \to \omega\eta n$ at 32 and 38 GeV/c. They state that this narrow state is observed at high $|t|$ in each of three independent data samples. A full-fledged partial-wave analysis has not been done yet but a preliminary study points to an exotic set of quantum numbers[d] $J^{PC} = 0^{--}$, 2^{+-}. If confirmed, this would constitute the first evidence of a J^{PC}-exotic state with $C = -1$.

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[c] F. Close and P. Page state that a gluonic hybrid should have a small non-zero coupling to S-wave quarkonia, *e.g.* $\rho\pi$—see their contributions elsewhere in this Proceedings. They point out further the suppressed channel could be enhanced, if the ρ is off the mass shell, as would be the case when it is the exchanged particle in $\pi^- p$ interactions at moderate to high beam momenta.

[d] In the flux-tube model of hybrids, the $J^{PC} = 0^{--}$ is not allowed in the lowest-order string excitations. Therefore, this state should occur at a higher mass than that of a $J^{PC} = 2^{+-}$ hybrid.

5 Other results

Pinder [30] gave a review on two new isoscalar $J^{PC} = 2^{-+}$ objects in the $\eta\pi^0\pi^0$ system. The analysis is based on the Crystal Barrel data on the reaction $\bar{p}p \to \eta\pi^0\pi^0\pi^0$ at rest, at 1.20 and 1.94 GeV/c. He finds the $\eta_2(1645)$ decaying into $a_2^0(1320)\pi^0$, at mass $1645 \pm 14 \pm 15$ MeV and width $180 \begin{smallmatrix} +40 \\ -21 \end{smallmatrix} \pm 25$ MeV. This state is, evidently, the isoscalar partner of the $\pi_2(1670)$. He finds in addition a higher mass $J^{PC} = 2^{-+}$ state $\eta_2(1875)$, at mass $1875 \pm 20 \pm 35$ MeV and width $200 \pm 25 \pm 45$ MeV, decaying into $f_2(1270)\eta$. Despite this decay mode, one may assign the $\eta(1875)$ as the mostly $s\bar{s}$ partner of the $\pi_2(1670)$ nonet. It may have been previously seen by the Crystal Ball collaboration [31] in the reaction $\gamma\gamma \to \eta\pi^0\pi^0$; however, their claimed decay modes are $a_0(980)\pi^0$ and $a_2(1320)\pi^0$. The nature of this state will remain uncertain until a study of the $K^*(890)\bar{K}$ decay mode is completed.

New results on the tensor state coupling to $\phi\phi$ have been presented by Palano [32] representing the Jetset collaboration. They have collected data on the formation process $\bar{p}p \to \phi\phi$ with the $\sqrt{s}$ ranging from 2.0 to 2.4 GeV at LEAR. A partial-wave analysis of the $\phi\phi$ system shows a strong $J^{PC} = 2^{++}$ with mass 2200 ± 10 MeV and width 90 ± 18 MeV. It is not certain how this state is related to the three glueball candidates claimed by Lindenbaum*et al.*[33] at masses 2010, 2300 and 2340 MeV. One thing is clear already; the $\phi\phi$ spectrum of Jetset drops off much more rapidly than that of the Lindenbaum data. Evidently, the $\bar{p}p$ formation process seems to excite the lower mass tensor states of Lindenbaum *et al.* more than the higher mass ones. Further analysis on the full data sample by the Jetset collaboration is eagerly awaited, since a tensor glueball is expected in the mass region 2.0–2.3 GeV.

A spin-4 $\eta\pi$ state has been reported by the GAMS collaboration,[26] from an analysis of the reaction $\pi^- p \to \eta\pi^0 n$ at 38 GeV/c. The state is measured to be at mass 2020 ± 25 MeV and width 220 ± 140 MeV. The dominant wave is found to be $|G_+|^2$ but also some non-zero $|G_0|^2$. Thus, this state is produced mainly by natural-parity exchange and could be identified with the $a_4(2040)$ seen previously [27] in $K\bar{K}$ and $\pi\pi\pi$.

6 Conclusions and future prospects

It is gratifying to see that a lot of progress has been made in recent years—both theoretically and experimentally—concerning hadrons in general and glueballs and hybrids in particular.

Hadron95 may the conference at which, by consensus, the scalar glueball has been sighted. Pennignton has commented on this extensively in his portion of the Conference Summary. If the $f_0(1500)$ is indeed a state which is mixed between quarkonia and a glueball,[34] then a tensor glueball should occur between 2.0–2.4 GeV. There are two candidates, the $\phi\phi$ states at 2010, 2300 and 2340 MeV, and the $\xi(2230)$ seen originally by MarkIII and rediscovered and extended by BES.[35] One expects two isoscalar $^3F_2$ states in this mass region.[36] The task of finding a tensor glueball, then, necessarily involves identifying the $^3F_2$ states.

There exists as yet no 'certified' J^{PC}-exotic state; all candidates are in need of confirmation. A $J^{PC} = 1^{-+}$ state at mass 1.3–1.4 GeV was claimed by GAMS and KEK in the $\eta\pi$ systems, and a $J^{PC} = 1^{-+}$ state at mass 2.0–2.2 GeV decaying into the $f_1(1285)\pi$ channel. According to the predictions of the flux-tube model,[37] a hybrid meson $q\bar{q} + g$ should couple preferentially to a P-wave and an S-wave quarkonia, and the predicted mass is in the range 1.85–2.3 GeV. It seems that the $f_1(1285)\pi$ state might be the one favored by the flux-tube model, but other decay modes such as $b_1(1235)\pi$ must be studied, before a firm confusion can be reached. In addition, the hybrids are expected to have substantial couplings to $K_1(1400)\bar{K}$, $K_1(1270)\bar{K}$ and $K_2^*(1430)\bar{K}$. Thus their nature and status will remain uncertain until all the $s\bar{s}$ systems are systematically explored.

The E/ι region harbors four states: $f_1(1440)$, $\eta(1400)$, $\eta(1460)$ and $h_1(1400)$. The $h_1(1400)$ is likely to be the $s\bar{s}$ partner of the $b_1(1235)$ nonet, but the rest are probably not ordinary quarkonia. The $f_1(1510)$ is surely the $s\bar{s}$ partner of the $a_1(1260)$ nonet, leaving the $f_1(1440)$ as a redundant state. This state may be a $K^*(890)\bar{K}$ molecule communicating with the $a_0(980)\pi$ channel.[38] The $\eta(1295)$ is the non-strange isoscalar partner of the first radially excited $^1S_0$ family. According to Model P2 of Godfrey and Isgur,[36] its $s\bar{s}$ partner should occur at mass 1.55 GeV, too high for either $\eta(1400)$ or $\eta(1460)$. Furthermore, the production characteristics of both suggest that they are mostly non-strange. The nature of these states is therefore uncertain at the moment.

It is clear that much further work is needed, if one is to have a better understanding of the gluonic hadrons as well as the many states in the mass region between 1.5 to 2.5 GeV which seem redundant in the $SU(3)$ classification of mesons. It is distressing to hear that the CERN LEAR machine and the CERN Omega Spectrometer will be shut down at the end of 1996. It is hoped that the CERN management will help initiate construction of another modern detector-facility soon—perhaps the proposed CHEOPS [39] in its expanded version. The BNL MPS facility will continue to be operated into the late 1990s, as are the facilities at IHEP/Protvino and IHEP/Beijing. The CEBAF and DAΦNE machines should shed light on the nature of the $f_0(980)$ and the $a_0(980)$, expected to be seen in the radiative ϕ decays. The BNL RHIC is expected to become operational in 1999. There exists an ongoing effort to use RHIC as a source of energy to study production of gluonic hadrons initiated by Pomeron+Pomeron, Pomeron+γ and $\gamma + \gamma$ fusion processes.

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