EXPERIMENTAL AND THEORETICAL LIMITS ON MASS OF A_1

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An attempt of estimation of the A_1-meson mass is undertaken. After a short review of the confusing experimental situation, the estimations, based on the SU(3) symmetry, nonrelativistic potential model with the Breit-type Hamiltonian spin structure and Regge pole phenomenology, are discussed. The A_1 mass in vicinity 1200 MeV is favoured.

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1. *Introduction*

After a decade of futile search for the isovector member of 1^{++} nonet expected from the quark model (QM), the last few years brought a paradoxal change in the situation: we have apparently too many candidates for the A_1 resonance. Which is the right one? What are the others?

In attempt to answer these questions we bring together new experimental information which has been accumulated in the last few years, in particular

i) spectroscopic data on the A_1 resonance,

ii) spectroscopic data on the other members of 1^{++} nonet, related to the A_1 problem through SU(3) symmetry,

iii) spectroscopic data on P-wave meson nonets (2^{++}, 1^{++}(A), 1^{+-}(B), 0^{++}) related to the A_1 problem through the spin structure of the nonrelativistic Breit-type Hamiltonian,

iv) production characteristics of some exclusive processes related to the A_1 problem through the Regge pole phenomenology.

In Section 2 most significant experiments on the A_1 production are shortly reviewed. Emphasis is put on the uncertainties in determination of the resonance position. In Section 3 the A_1-mass is estimated on the basis of SU(3) relations for resonance mass and D and E decay width. Section 4 is devoted to the Breit Hamiltonian model for spin structure

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of P-wave mesons and its implications for A_1 resonance position. In Section 5 indirect estimations of the A_1 mass based on the Regge pole phenomenology are discussed. Section 6 contains general conclusions.

2. *Experimental status of the A_1 ($J^{PC} = 1^{++}$) resonance*

In the last few years a considerable amount of experimental information on A_1 ($J^{PC} = 1^{++}$) state has been accumulated. A_1 can finally be considered as a well established meson, however, the determination of its parameters is far from being settled. In fact,

TABLE I

Most significant experiments producing $J^{PC} = 1^{++}$ 3π state

m_{A_1} [GeV]	Γ_{A_1} [GeV]	Reaction	Reference
1.04 ± 0.013	0.23 ± 0.05	$K^-p \to \pi^+\pi^-\pi^-\Sigma^+$	[1], [3]
$0.9 < m < 1.2$	$0.5 < \Gamma < 0.6$	$\tau \to \rho\pi\nu$	[4], [5], [6]
1.28 ± 0.03	~ 0.3 GeV	$\pi^-p \to \pi^+\pi^-\pi^-p$	[9], [10]
1.24 ± 0.08	0.38 ± 0.10	$\pi^-p \to \pi^+\pi^-\pi^0\Delta^{++}$	[16]

the data indicate that in $1.0 - 1.4$ GeV region 1^{++} wave of the 3π system contains more than just $\bar{q}q$ QM resonant state. In Table I we present the compilation of the A_1-mass and width estimations from the most significant experiments[1].

The lowest mass signal has been seen in the backward production in K^- beam [1]. The K^- beam experiment has enough statistics to project out different partial waves [3]. The resonance nature of the intensity peak in the 1^+S wave at 1040 MeV is confirmed by an appropriate phase motion.

In two e^+e^- experiments the semileptonic decay $\tau \to A_1\nu_\tau$ seems to have been discovered [4, 5]. The $\varrho^0\pi^\pm$ mass distribution peaks at $m \simeq 1.1$ GeV. It is only marginally described by a τ decay into nonresonating $\varrho\pi$ S-wave state (χ^2 probability $= 1\%$). If, however, a Breit-Wigner resonance is included the peak can be well reproduced for parameters like $0.9 < m < 1.2$ and $0.4 < \Gamma < 0.5$ GeV. The spin parity analysis of the $\varrho^0\pi$ final state [6] using the density in the 3π Dalitz-plot confirms $J^P = 1^+$ assignment and shows that other contributions are small. The branching ratio $B(\tau \to \nu\varrho\pi) = 0.108 \pm 0.026$ is in good agreement with the theoretical prediction [7].

The experiments producing A_1 diffractively are most significant from the statistical point of view but also most difficult to analyze. A major obstacle to the accurate theoretical analysis of A_1 is its production in the presence of the large non-resonant Deck-type background. A detailed dynamical theory of such complicated phenomena does not exist so the A_1 mass estimation is as good as a phenomenological model involved in the data description.

[1] For full list of the experiments claiming A_1 found see Ref. [2].

The ACCMOR experimental data presented in Refs [9, 10] contain unprecedented statistics of almost 600000 events of the reaction $\pi^- p \to \pi^-\pi^-\pi^+ p$ and show the resonance effect in the 1^+S ($\varrho\pi$) partial wave beyond any doubt.

The forward motion of the 1^+S phase by $\sim 80°$ in 1.1 – 1.5 GeV region has been shown by referring 1^+S0^+ to 2^+D1^+ ($J^P LM^\eta$ notation) which is dominated by the A_2 meson, thus its absolute phase is known.

Secondly, there is a systematic change in shape of the 1^+S intensity as a function of t'. From low to high momentum transfers the qualitative change is from a broad peak in the 1.1 GeV region to a flat top from 1.1 to 1.3 GeV with rapid fall-off to, finally, a narrower peak in the 1.3 GeV region.

The systematic change in shape of the 1^+S intensity as a function of t' and the observed large phase increase give an indication of production of a resonant object of mass $\simeq$ 1.3 GeV with a rather flatter t' distribution than that of a coherent background. Such interpretation of the data is supported by the model in which a background amplitude provided by the Deck process is rescattered through a resonance which also may be produced directly [11]. Fits require a resonance with parameters given in Table I. "Resonance + rescattered Deck" model cannot be considered as a unique interpretation of the diffractive production.

It has been suggested by several authors that the Deck mechanism is equivalent to a four quark interaction [12–15]. In this picture the Pomeron picks up a sea quark-antiquark pair to create the 4q exotic state. In Ref. [15] the $J^P = 1^+$ three pion production amplitudes obtained from the most recent diffractive [9, 10], charge exchange [16] and backward production experiments are analyzed. The amplitudes contain three pieces interpreted in terms of $q\bar{q}$, $2q2\bar{q}$ and $3q3\bar{q}$. The $q\bar{q}$ piece gives rise to the A_1 resonance whose parameters are $m_{A_1} = 1230 \pm 30$ MeV, $\Gamma_{A_1} = 350 \pm 60$ MeV. The interesting feature of this work is the attempt of consistent interpretation of the two apparently different physical objects: "diffractive A_1" ($m_{A_1} \simeq 1280$ MeV) and "backward A_1" ($m_{A_1} \simeq 1040$ MeV). Low mass backward A_1 is an effect caused by strong $q\bar{q}$ and $2q2\bar{q}$ interference.

The recent paper of Bellini et al. [17] brings essentially new information which sheds a new light on the whole problem. A partial wave analysis of the 3π system produced on nuclear targets shows that the relative phase $1^+S - 0^-P$ varies across the A_1 region much more than in the data from protons. The data on light nuclei are rather similar to those obtained from protons. The phase motion increases systematically with the target mass from about 70° on light nuclei up to about 130° on heavy ones. No clear explanation of this effect exists yet. However, it shows that "rescattered Deck + direct resonance production" interpretation of the diffractive production data does not contain the whole truth. The idea that the nucleus can absorb in different ways the different states ($q\bar{q}$ and $2q2\bar{q}$ for example) and the absorption effects increase with atomic weights seems to us most appealing.

Finally we should mention another source of the ambiguity in mass determination inherent to the partial wave analysis method. According to Ref. [17] the results of the partial wave analysis of the 3π system strongly depend on the parametrization of $\pi\pi$ phase shifts describing the 0^+ dipion. Using the $\pi\pi$ phase shifts of Ref. [18] results in a peak of

1^+S mass about 25% higher and displaced by ~100 MeV to higher $m_{3\pi}$ mass when compared with the partial wave analysis employing "ε parametrization" (broad Breit-Wigner shape). As the "true" description of the 0^+ dipion is not known one has to argue very carefully about the shape of the 1^+S mass distribution.

To summarize the results of studies of the diffractive production of the 3π system in the A_1 region we can say that the resonance effect has been shown beyond any doubt. However, the resonance parameters determination has to be treated with caution. Our short review of the experimental situation concerning A_1 meson shows that there is a lot of resonance-like activity in 1.04–1.3 GeV region of mass of the 3π 1^+S state. However, information coming from different experiments seems to be contradictory. A consistent treatment of all these phenomena probably requires more than just single resonance + background [15]. So finally, where is the A_1 meson? We try to answer this question in the next two Sections without resorting to the direct information on A_1 mass.

3. *SU(3) structure of the 1^{++} multiplet*

Since suitable candidates for members of a 1^{++} nonet have been established, several discussions of their SU(3) assignment were carried out [19, 20, 10, 21]. In our approach we determine the 1^{++} nonet mixing angle independently of the A_1 meson mass. Then, the A_1 mass is estimated through the Okubo-Gell-Mann (OGM) mass formula.

The candidates for 1^{++} nonet members are: $A_1(I = 1)$, D(1285), E(1420) $(I = 0)$ and $Q_A(\approx 1310)$ $(I = 1/2)$. The $I = 1/2$ member of the nonet Q_A does not appear as a physical state due to mixing with the opposite C parity state Q_B [22, 23], where by C parity we mean the generalized C parity equal to the genuine C parity of the neutral members of the nonet [48]. The physical states Q_1, Q_2 have firmly established masses [24, 25] but the $Q_A - Q_B$ mixing angle is subject to some uncertainty.

From the quark model point of view, an ideally mixed nonet would be most satisfactory. The quark model relation

$$m_D^2 + m_E^2 = 2Q_A^2 \tag{3.1}$$

implies $m_{Q_A} \simeq 1.35$ GeV. The relation

$$m_{Q_A}^2 = \frac{m_{Q_1}^2 + m_{Q_2}^2}{2} + \frac{m_{Q_1}^2 - m_{Q_2}^2}{2} \cos 2\theta_{AB}, \tag{3.2}$$

where θ_{AB} is the $Q_A - Q_B$ mixing angle, implies $m_{Q_A} < 1.34$ GeV for $\theta_{AB} > 45°$. Putting the upper limit for Q_A mass and the A_1 mass as given in Refs [9, 10] we arrive at A-nonet with $m(A_1) = 1280$, $m(D) = 1285$, $m(Q_A) = 1340$ and $m(E = D') = 1420$ MeV which indeed satisfies nearly exactly the ideal angle mass mixing. Such a picture suggested in Refs [10, 21], although appealing, seems to be unlikely for the following reasons:

i) The relation $m_{Q_A}^2 = \dfrac{m_{Q_1}^2 + m_{Q_2}^2}{2}$ is satisfied for $\theta_{AB} = 45°$. Both high statistics experiments $\overline{K}p \to \overline{K}\pi^+\pi^-p$ [24, 25] give evidence for a mixing angle in excess of 45°, i.e. $m_{Q_A}^2 < \frac{m_{Q_1}^2 + m_{Q_2}^2}{2}$. As shown in Ref. [25] the amplitudes of direct production of Q_1 and Q_2 via Pomeron exchange (f_1 and f_2 respectively) are related by

$$f_1 = -f_2 \operatorname{tg} \theta_{AB}$$

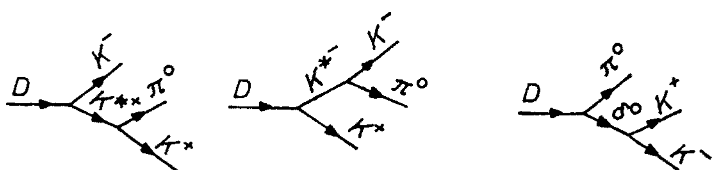
provided that the Pomeron is a $C = +1$ object. At low t where the helicity conserving Pomeron dominates the two $M = 0$ production amplitudes are indeed approximately 180° out of phase and their ratio corresponds to the mixing angle $\simeq 65°$. The average value of θ_{AB} given by Ref. [25] implies $m_{Q_A} \simeq 1.31$ GeV, far from the value predicted by the quark model relation (3.1).

ii) The spin structure predicted by the Breit-type Hamiltonian [26] indicates a large gluon component of D meson. This point will be discussed in detail in the next Section.

The singlet-octet mixing angle θ_{DE} can be estimated independently of relation (3.1) and the OGM formula

$$4m_{Q_A}^2 - m_{A_1}^2 = 3m_8^2 \tag{3.3}$$

using measured widths and branching ratios for D and E decays and interdependence between them based on SU(3).



a b c

Fig. 1. The diagrams used to approximate the decay $D \to K^+K^-\pi_0$

To describe three-body decays of $D \to K\bar{K}\pi$ and $E \to K\bar{K}\pi$ we use the formalism of Ref. [27]. It is an isobar type model in which the isobar may be a virtual state. An analogous model for ϱ domination of ω decay is known to be successful. Each contribution is calculated as a correctly normalized Feynman diagram. We assume that only important modes contributing to D and E decays into $K\bar{K}\pi$ are $K\bar{K}^*$ and $\delta\pi$ (Fig. 1). Further we assume that the D-wave does not contribute significantly to $1^+ \to 1^-0^-$ decays. This assumption is consistent with experimentally observed and theoretically predicted D/S ratio in $A \to \varrho\pi$ decays. Integrating numerically over the Dalitz plot we arrive at the following expressions for D and E decay width into $K\bar{K}\pi$ as a function of $\Gamma(D \to \delta\pi \to \eta\pi\pi) = \Gamma_{\eta\pi\pi}$, g_A — SU(3) reduced coupling constant and singlet-octet mixing angle θ

$$\Gamma(D \to K\bar{K}\pi) = 0.086\Gamma_{\eta\pi\pi} + 1.47 g_A^2 \sin^2\theta$$

$$+0.648\sqrt{\Gamma_{\eta\pi\pi}}\, g_A \sin\theta, \tag{3.4}$$

$$\Gamma(E \to K\bar{K}\pi) = 64.5 g_A^2 \cos\theta$$

$$+0.35\Gamma_{\eta\pi\pi} \operatorname{tg}^2(\theta - \theta_I) + 2.83 g_A \sqrt{\Gamma_{\eta\pi\pi}} \operatorname{tg}(\theta - \theta_I). \tag{3.5}$$

In the above formulae θ_I is the ideal mixing angle $\operatorname{tg}\theta_I = \frac{1}{\sqrt{2}}$. g_A is defined in such a way that in narrow width isobar approximation (quasi-two body)

$$\Gamma(A \to BC) = \varrho(M_A)C^2_{ABC}g^2_A, \tag{3.6}$$

where $\varrho(M_A)$ is a kinematic factor containing the phase space and centrifugal barrier factor:

$$\varrho(M_A) = q^{2L+1}/M^2_A. \tag{3.7}$$

C_{ABC} is an appropriate SU(3) isoscalar factor[2].

The total E width $\Gamma(E)$ is given by

$$\Gamma(E) = \Gamma(E \to K\bar{K}\pi) + \Gamma(E \to \eta\pi\pi)$$

as no $E \to 4\pi$ decays have been observed.

$$\Gamma(E \to \eta\pi\pi) = 2.54 \cdot \Gamma_{\eta\pi\pi} \cdot \operatorname{tg}^2(\theta - \theta_I). \tag{3.8}$$

In the derivation of formulae (3.4) and (3.5) we have additionally assumed the SU(3) relation for $\delta K\bar{K}$ and $\delta\eta\pi$ coupling constants $g_{\delta K\bar{K}}/g_{\delta\eta\pi} = -\sqrt{\frac{3}{2}}$. This assumption seems to be solidly backed by the analysis of the high statistics data performed in Ref. [28]. Also a recent analysis of the $\eta' \to \eta\pi\pi$ decay [29] makes four quark assignment of the δ-resonance rather unlikely.

In the derivation of formulae (3.5) and (3.8) an additional quark model assumption about the singlet part of the interaction has been made (unlike in formula (3.4) where only the octet part ($K\bar{K}^*$ decay) and the SU(3) relation for δ decay are involved). In the SU(3) symmetry, the singlet coupling constant is quite independent of the octet coupling and it is the quark model which constrains them so that the Okubo-Iizuka-Zweig (OIZ) rule [30] is fulfilled. So the gluon component of D and E might change relations (3.5) and (3.8) as far as $\delta\pi$ and $K\bar{K}^* - \delta\pi$ interference terms are concerned. On the other hand, the first term of formula (3.5) representing $K\bar{K}^*$ decay contributes > 95% for mixing angles < 50°, consistently with the lack of observation of the $E \to \delta\pi \to \eta\pi\pi$ decay in the high statistics experiment $\pi^- p \to \eta\pi\pi n$ [31] which observes 3000 $\eta' \to \eta\pi\pi$ decays[3]. This suggests that indeed E decays almost exclusively into $K\bar{K}^*$ channel and formula (3.5) reflects almost correctly the E meson width dependence on the singlet octet mixing angle.

Using formulae (3.4), (3.5), (3.8) and the measured quantities [2]

— $\Gamma(D)$ (D meson total width) = 27 ± 10 MeV,

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[2] $1^+ \to 1^- 0^-$ decay is described by two independent coupling constants which can be reduced to a single one under the assumption of the vanishing D wave.

[3] The only experiments in which a significant signal in $\eta\pi\pi$ at 1.4 GeV has been reported are $p\bar{p} \to \pi^+\pi^-(\eta\pi\pi)_{1.4}$ [32] and $\psi \to \gamma(\eta\pi\pi)_{1.4}$ [33] largely in $\psi \to \gamma\delta\pi \to \gamma\eta\pi\pi$ mode. The recent analysis [34] has shown that in the $\psi \to \gamma(\eta\pi\pi)_{1.4}$ decay the J^P assignment of $(\eta\pi\pi)_{1.4}$ object is 0^- rather than 1^+. It has been suggested [35] that there are two objects at the mass ≈ 1400 MeV: normal $q\bar{q}$ 1^{++} state decaying almost exclusively into $K\bar{K}^*$ and the glueball 0^{-+} G (1440) seen in $p\bar{p}$ interaction and ψ radiative decay.

— Γ(E) (E meson total width) = 50 ± 10 MeV,
— R($\delta\pi$) (branching ratio D $\rightarrow$ $\delta\pi$) 0.36 ± 0.07,
— R($K\bar{K}\pi$) (branching ratio D $\rightarrow$ $K\bar{K}\pi$) 0.1 ± 0.02,
— g_A (reduced SU(3) coupling constant from Ref. [25]) = 1.32 ± 0.11

we fitted the mixing angle θ allowing g_A to vary as a free parameter. The result is

$$\theta = 38 \pm 6°, \quad g_A = 1.19 \pm 0.06.$$

Using the fitted values of θ and g_A we get Γ(E) = 57 MeV. It appears that the mixing angle is constrained mainly by relatively well measured R($K\bar{K}\pi$) branching ratio as shown in Fig. 2. In Fig. 3 we show the A_1 meson mass dependence on θ as given by the OGM mass formula for $m_{Q_A} = 1.31 \pm 0.015$, $m_E = 1.42$, $m_D = 1.285$ GeV. The width of the band corresponds to an error on Q_A mass (formula (3.3) is much less sensitive to D and E masses). From Fig. 2 we estimate $m_{A_1} = 1.1 \pm 0.13$ GeV. We arrive at the conclusion that the A_1 nonet is almost ideally mixed, however it is considerably lighter than D.

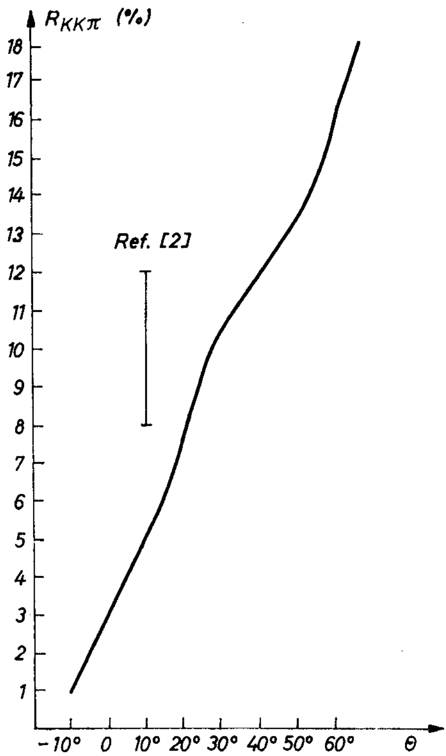


Fig. 2

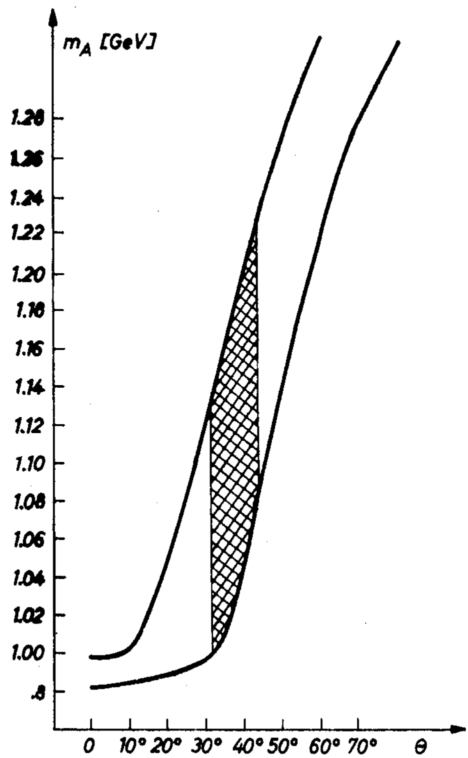


Fig. 3

Fig. 2. Branching ratio for D $\rightarrow$ $K\bar{K}\pi$ decay as a function of singlet-octet mixing angle

Fig. 3. A_1-mass as a function of the singlet-octet mixing angle θ given by the GMO formula. Band width corresponds to the errors on Q_A mass. Shaded area corresponds to the range of values allowed by errors Q_A and θ

This departure from the quark model in which one expects a mass degeneracy for the ideal mixing might be interpreted in terms of a gluon component [26].

When discussing the SU(3) relations for 1^{++} nonet branching ratios it is interesting to note peculiarity of P-wave decays. In Refs [24] and [25] 30% branching ratio of Q_1 to $\kappa\pi$ have been observed. Using the mixing formalism, the coupling of Q_A to $\kappa\pi$ may be determined and used to predict the widths of other P-wave decays $1^{++} \to 0^{+}0^{-}$ where 0^{+} denote scalar mesons belonging to the same octet. In particular, we get

$$\Gamma(Q_A \to \kappa\pi) = \varrho(m_{Q_A}) \sin^2\theta \tfrac{9}{20} g_8^2,$$

$$\Gamma(A_1 \to \varepsilon_8\pi) = \varrho(m_{A_1}) \tfrac{4}{20} g_8^2,$$

$$\Gamma(D \to \delta\pi) = \varrho(m_D)\left[-\sqrt{\tfrac{12}{20}}\, g_8 \sin\theta + \sqrt{\tfrac{3}{8}}\,(g_1 \cos\theta + \tilde{g}_1(m_D))\right]^2,$$

$$\Gamma(E \to \delta\pi) = \varrho(m_E)\left[\sqrt{\tfrac{3}{8}}\,(g_1 \cos\theta + \tilde{g}_1(m_E)) + \sqrt{\tfrac{12}{20}}\, g_8 \sin\theta\right]^2,$$

where the kinematical factor $\varrho(M)$ given by formula (3.7) is averaged over the final state resonance width. ε_8 is the octet part of the $\varepsilon(800)$. g_8 and g_1 are octet and singlet couplings to $q\bar{q}$ component of D and E whereas $\tilde{g}_1(M)$ is a singlet coupling which goes beyond quark model (for example a coupling to gluon component). g_8 and g_1 are related in such a way that in the case of ideal mixing E would decouple from $\delta\pi$ if $\tilde{g}_1(m_E) = 0$. The allowance made for a gluon component in the singlet coupling constant renders P-wave decays of D and E practically unpredictable. Vice versa, deviations from the quark model predictions for these decays can be interpreted in terms of $\tilde{g}_1(M)$. Using the results of Ref. [25] for $B(Q_1 \to \kappa\pi)$, Γ_{Q_1} and Q_A-Q_B mixing angle we get for the ideal mixing $\Gamma(D \to \delta\pi) \simeq 340$ MeV, $\Gamma(E \to \delta\pi) = 0$ and $\Gamma(D \to \delta\pi)+\Gamma(E \to \delta\pi) > 340$ MeV independently of the mixing angle, provided $\tilde{g}_1(M) = 0$. This result is in complete disagreement with experiment for $D \to \delta\pi$ and indicates a large gluon component for D meson and small or negligible one for E meson. It seems that such conclusion is to some extent confirmed by the results presented in the next Section.

For A_1 at 1.2 GeV and ε parametrized as Breit-Wigner resonance at 760 MeV and 400 MeV wide we get $\Gamma(A_1 \to \varepsilon_8\pi) = 45$ MeV. Assuming that ε_8 content in ε corresponds to the ideal mixing we get the agreement with $\Gamma(A_1 \to \varepsilon\pi) = 18$ MeV [4] determined from A_1 exchange strength in the reaction $\pi^+p_\uparrow \to \varepsilon\pi$ [36].

All these considerations are based on the assumption that ε, δ and κ are $q\bar{q}$ states belonging to the same SU(3) octet. It cannot be taken for granted. In fact, the prevailing opinion is that the low lying 0^{++} states are $qq\bar{q}\bar{q}$ objects [12, 37, 38]. It is interesting to note what are the consequences of $qq\bar{q}\bar{q}$ assignment of scalar mesons for $1^{++} \to 0^{-}0^{+}$ decays.

In the first approximation there should be no such decays, as all quarks in the scalar $qq\bar{q}\bar{q}$ object are in the relative S-wave state [37], in particular the $A_1\varepsilon\pi$ coupling should vanish. Such a conclusion is clearly in contradiction with the appreciable polarization observed for S-wave $\pi\pi$ system in the polarized target data $\pi^-p_\uparrow \to \pi^+\pi^-n$ [39].

[4] The result $\Gamma(A_1 \to \varepsilon\pi) = 50$ MeV quoted originally in [36] is based on $\varrho(M_A)$ not averaged over ε width.

Let us however assume that the second order transitions of the type $1^+(q\bar{q}) \to 0\,(q\bar{q})0^+(qq\bar{q}\bar{q})$ exist. If δ is $qq\bar{q}\bar{q}$ system coupled through $s\bar{s}$ piece to D and E then $\Gamma(E \to \delta\pi)/\Gamma(D \to \delta\pi) \gg 1$. This observation [29] has been used as an argument for $q\bar{q}$ interpretation of the δ meson.

To conclude this Section let us reiterate its main points:

i) The singlet octet mixing angle estimated from the branching ratios for S-wave D and E decays is close to ideal.

ii) The A_1 mass estimated from OGM mass formula $m_{A_1} = 1.1 \pm 0.13$ is considerably lower than the D mass whereas one expects the $D-A_1$ degeneracy for ideally mixed nonet. This fact seems to indicate a gluon component in the D meson.

iii) The peculiarity of P-wave decay $D \to \delta\pi$ confirms the above mentioned hypothesis.

4. *Spin structure of the P-wave mesons*

A considerable success in description of hadronic state has been achieved from a mixture of phenomenological and theoretical considerations based on QCD [40, 41, 26]. Spin dependent corrections to the level structure based on atomic-type models for valence quarks proved to be a quite powerful tool in describing the mass spectrum of baryons and mesons. In this Section we discuss most recent spectroscopic data for P-wave mesons along the lines of Ref. [26], emphasizing its bearing on the A_1 mass.

We construct a Breit-type Hamiltonian for a spin dependent quark-antiquark interaction which characterizes the effective behaviour of the underlying QCD after colour sums have been performed. It is of the form [26]

$$H = v_C(r) + \frac{1}{m_1 m_2} v_T(r) S_{12} + \frac{4}{m_1 m_2} v_S(r) \vec{S}_1 \cdot \vec{S}_2$$
$$+ \left[\frac{1}{m_1 m_2} v_1(r) + \tfrac{1}{2}\left(\frac{1}{m_1^2} + \frac{1}{m_2^2}\right) v_2\right] \vec{L} \cdot \vec{S}$$
$$+ \tfrac{1}{2}\left(\frac{1}{m_1^2} - \frac{1}{m_2^2}\right) v_2(r) \vec{L} \cdot (\vec{S}_1 - \vec{S}_2). \tag{4.1}$$

Eq. (4.1) provides a very good understanding of the meson spectroscopy with the assumption that the matrix elements of v_1, v_2, v_T and v_S are SU(3) invariant. In other words, the dominant SU(3) breaking is assumed to have its origin in the kinematical factors of constituent quark masses. The constituent quark masses may be estimated [40] from the masses of the S-wave mesons and baryons (ratio of strange and nonstrange quark masses) and the observed magnetic moments (nonstrange quark masses). The data are consistent with $m_u = m_d \simeq 330$ MeV and $m_s \simeq 500$ MeV. In Table II we list the P-wave meson states. There are no unambiguously identified $^3P_0$ pure $q\bar{q}$ states but we included into Table II the meson $\delta(980)$ which seems to be the best candidate.

Eq. (4.1) leads [26] to the following relations

$$m(^1P_1)-m(^3P_1) = \left[\frac{1}{m_1m_2}v_1+\tfrac{1}{2}\left(\frac{1}{m_1^2}+\frac{1}{m_2^2}\right)v_2\right]-\frac{2v_T}{m_1m_2}-\frac{4v_S}{m_1m_2},$$

$$m(^3P_1)-m(^3P_0) = \left[\frac{1}{m_1m_2}v_1+\tfrac{1}{2}\left(\frac{1}{m_1^2}+\frac{1}{m_2^2}\right)v_2\right]+\frac{6v_T}{m_1m_2},$$

$$m_{Q_1}+m_{Q_2} = m_{Q_A}+m_{Q_B},$$

$$(m_{Q_2}-m_{Q_B})(m_{Q_B}-m_{Q_1}) = 2\left[\tfrac{1}{2}\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)v_2\right]^2. \tag{4.2}$$

We will try to find out the implications of the above formulae for the A_1 mass.

At first, we observe that the Q_A-Q_B mixing angle $\theta_{AB} > 45°$ (see discussion in the previous Section) implies $m_{Q_B} > m_{Q_A}$ and $m_{A_1} < m_B = 1231$ MeV unless the SU(3) invariance of matrix elements is broken. Secondly, assuming that δ(980) is indeed $0^{++}q\bar{q}$ state we get

$$m(^3P_1) = m_{A_1} = 3m_B-\tfrac{5}{3}m_{A_2}-\tfrac{1}{3}m_\delta+\frac{12v_S}{m_u^2},$$

$$m_{A_1} \approx 1170\pm15+\frac{12v_S}{m_u^2}\text{ MeV}.$$

For the P-wave state the spin-spin interaction should be rather small, therefore it is unlikely that the A_1 mass exceeds considerably 1200 MeV. If we set $m_{A_1} = 1171$ MeV we will find that at $\theta_{AB} = 55.5°$ (corresponding to $m_{Q_A} = 1315$ MeV and $m_{Q_B} = 1365$ MeV) relations (4.2) (for $I = 1$ and $I = 1/2$) are nicely fulfilled with the matrix elements (in 10^6 (MeV)^3) $v_S = 0$, $v_T = 1.8$, $(v_1+v_2) = 10.1$, $|v_2| = 17.7$.

TABLE II

Light quark P-wave meson states

Isospin	$^3P_2$	$^1P_1$	$^3P_1$	$^3P_0$
$I = 1$	$A_2(1317)$	B(1235)	$A_1(?)$	δ(980)
$I = 1/2$	K*(1434)	$Q_B(1370)$	$Q_A(1310)$	
		$Q_1(1410)$	$Q_2(1270)$	
$I = 0$ $(u\bar{u}+d\bar{d})$	f(1274)	H(1130−1190)	D(1285)	
$I = 0$ $(s\bar{s})$	f′(1515)	?	E(1420)	

Obviously some deviations from the SU(3) symmetry are expected however to get $m_{A_1} = 1285$ MeV, as required by the quark model we would need $(v_S)_{I=1/2} \approx 0$ and $(v_S)_{I=1} \approx 1$, i.e. 10% of the spin orbit force what seems a rather unlikely hypothesis.

TABLE III

Matrix elements of the Breit-type Hamiltonian for P-wave meson states obtained from Table II and Eqs (4.2). For $I = 1/2$ a combination of matrix elements $v_1 + 1.09\,v_2$ is determined, instead of $v_1 + v_2$. Units 10^3 MeV^3

Isospin / Matrix element	$I = 1/2$	$I = 1$	$I = 0$ ($u\bar{u}$)	$I = 0$ ($s\bar{s}$)
$E(^1P_1 - E(^3P_1)$				
$\{(v_1+v_2)-2v_T-4v_S\}$	8.2	6.5	−10.3	
$E(^3P_2)-E(^1P_1)$				
$\{(v_1+v_2)-0.4v_T+4v_S\}$	10.7	8.9	8.7	
$E(^3P_2)-E(^1P_1)$				
$\{2(v_1+v_2)-2.4\,v_T\}$	18.9	15.4	−1.6	23.5
$\|v_2\|$	17.7			

Let us turn to $I = 0$ sectors. In Table III the matrix elements obtained from Table II and formulae (4.2) are tabulated. We observe a strong symmetry violation. Its restortion would require the D meson mass below H(1190), around 1100 MeV. In Ref. [26] it has been suggested that the behaviour of $I = 0$ ($u\bar{u}+d\bar{d}$) states qualitatively different from $I = 1$ and $I = 1/2$ states might indicate their significant gluon content.

In conclusion, the Breit-type Hamiltonian model for spin structure of P-wave states favours the mass of A_1 meson below 1200 MeV.

5. *Indirect estimations of the A_1 mass*

Processes in which the Regge-pole exchange with A_1 quantum numbers can be separated and measured give opportunity to indirect estimation of the A_1 meson mass. This type of argumentation can be considered rather shaky, nevertheless it contributes to a conclusion consistent with others presented in this paper.

Evidences for the Regge-pole exchange amplitudes with the A_1 quantum numbers have been reported in the reactions $\pi^- p_\uparrow \to \pi^+\pi^- n$ [39] and $p_\uparrow p_\uparrow \to pp$ [43]. If we interpret these data in terms of the A_1-Regge pole exchange, information about A_1-trajectory, hence A_1-mass, can be extracted.

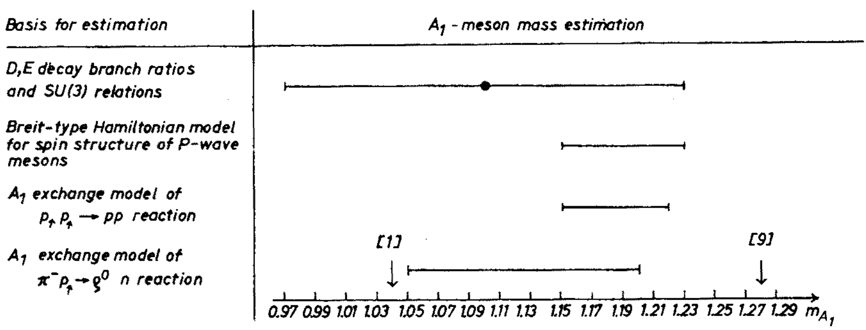
In the reaction $\pi^- p_\uparrow \to \varrho^0 n$ a large polarization has been observed at low t values. The Regge-pole interpretation of these data was presented in Ref. [36]. The A_1NN coupling constant has been determined in agreement with the A_1 meson dominance of the axial weak current [43] under the assumption that the intercept of the A_1-trajectory $\alpha^0_{A_1} \approx 0$. Provided that the current algebra predictions are correct within the factor 2 we can put the limits $\alpha^0_{A_1} \approx 0.0 \div -0.2$. Assuming the standard trajectory slope $0.8 \div 0.9$ we get $m_{A_1} = 1050 \div 1200$ MeV. Values around the upper limit would be preferred, as for the well determined unnatural parity trajectory B, $\alpha'_B \simeq 0.82$.

The NN elastic scattering with polarized beam and target also gives an opportunity to extract the A_1 exchange. In this process the difference between the total cross-sections for parallel and antiparallel spin orientations measures directly a contribution from A_1+Z trajectories [44]. If we assume the A_1 exchange to be the major contribution to $\Delta\sigma_L = \sigma_T(\frac{1}{2},\frac{1}{2}) - \sigma_T(\frac{1}{2},-\frac{1}{2})$ its measured value can be related to the $A_1N\bar{N}$ coupling constant and its energy dependence determines the intercept of the A_1-trajectory. Measurements of $\Delta\sigma_L$ at 3, 6 and 12 GeV [42] give $\alpha'^{0}_{A_1} = -0.19$ and $g_{A_1N\bar{N}}$ consistent with the meson dominance of the axial weak current. Thus our estimate of the A_1 mass is $m_{A_1} = 1.15-1.22$ GeV. Crucial to the above argument is the question of the exchange degeneracy of A_1 and Z trajectories. This point has been extensively discussed in Ref. [36].

6. *Conclusions*

In previous Sections various estimates of the A_1-meson mass have been carried out. We collect them in Table IV. A quick inspection leads to the conclusion that A_1 has to be placed in close vicinity of 1200 MeV, probably below it. For backwardly produced $A_1(1040)$ and diffractive $A_1(1280)$ an interpretation has yet to be found, probably beyond the scope of the quark model. The first attempt in this direction has already been made [15].

TABLE IV



Once we assign to the $q\bar{q}$ 1^{++} $I=1$ state a mass around 1200 MeV, immediately arises the problem of the D(1285) mass. In the quark model the $I=0$ $u\bar{u}+d\bar{d}$ state is mass degenerate with the $I=1$ $u\bar{u}-d\bar{d}$ state. The interpretation through a gluon component in $I=0$ state has been proposed [26] but the detailed explanation has yet to be found.

It is interesting to note that our estimate of the A_1 mass is consistent with QCD sum rules [46] giving [7] $m_{A_1} = 1.15 \pm 0.04$ GeV.

It is clear that full understanding of the 1^{++} nonet requires further study on experimental as well as theoretical side.

From the experiment we expect an unambiguous determination of the A_1 parameters in the first place. Probably the best prospects offers the $\tau \to A_1\nu$ decay for which substantial statistics should be accumulated in coming years of the PETRA operation. The possibility of clear discernment of the A_1 meson exists in experiments at very high energy investigating the coherent production of 3π states on nuclei in the region where the Primakoff process ($\gamma\pi \to A_1$) dominates over the hadronic background [45].

Phenomenological problems concerning 1^{++} nonet states certainly cannot be classified as academic. It is complicated dynamics of the light rather than heavy quark meson states where modern theoretical tools like QCD sum rules [46] or lattice gauge Monte Carlo calculations [47] can be fully put in test.

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