Ref.TH.2435-CERN

THREE JET STRUCTURES IN THE DECAY OF HEAVY QUARKONIUM STATES

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A B S T R A C T

We study the possibility that heavy 1^{--} quarkonium states decay hadronically by disintegrating into three "gluon jets". Energy and angular distributions are investigated. The importance of radiative decays into a single photon and two gluon jets is emphasized.

Ref.TH.2435-CERN

6 December 1977

1. INTRODUCTION

Within the QCD approach to hadrodynamics the hadronic decay of heavy quark-antiquark $C_n = -1$ vectormesons (e.g. $\psi(J)$ meson) proceeds via the annihilation of the $Q\bar{Q}$ -system (Q : heavy quark) into gluons which in turn proceed to materialize into ordinary hadrons. The simplest hypothesis is to suppose that the total annihilation rate is given by the annihilation of the $Q\bar{Q}$ -system into three massless color octet gluons, which turn with probability one into the final hadronic system ¹⁾ (for a justification of this approach see e.g. ref. (2)). It is well-known that the annihilation rate calculated this way in lowest order QCD perturbation theory according to the QCD analog of the Ore-Powell formula ³⁾ for ortho-positronium decay agrees with experiment ($\psi(J)$ decay) if $\kappa = g_{st}^2/4\pi$ (g_{st} : QCD quark-gluon coupling constant) is chosen to be about 0.2.

It is not clear at the moment, if the three-gluon decay formula can be applied for the $\psi(J)$ decay. It is quite possible that this decay is dominated by resonances in the three-gluon channel ("glue balls") in which case the application of lowest order perturbation theory is incorrect. ²⁾ The situation is expected to be much cleaner in case of very heavy vectormesons, for example the T -meson discovered recently ⁴⁾, or of yet heavier states to be discovered in the future.

In this paper we should like to point out that interesting new effects (jet structures etc.) are expected to be seen in the decay of very heavy $J^{PC}=1^{--} \bar{Q}Q$ states ("quarkonium") if the three gluon decay hypothesis is indeed correct. We suppose that not only the total annihilation rate but more detailed properties of the final hadronic state (jets, energy distributions, angular distributions) can be abstracted from the lowest order QCD formula. If our conjecture is correct, the study of heavy quarkonium decay in e^+e^- -annihilation experiments will provide us in the near future with rather detailed tests of QCD and its relevance for hadrodynamics.

2. HADRONIC DECAY OF $1^{--} \bar{Q}Q$ STATES.

Let us first recall the Ore-Powell formula applied to quarkonium decay into three gluons, which gives

$$\Gamma^h(V_{\bar{Q}Q} \rightarrow \text{hadrons}) / \Gamma(V_{\bar{Q}Q} \rightarrow e^+e^-) \quad (1)$$

$$= 5/18 \cdot \frac{\pi^2-9}{\pi} \cdot \frac{\kappa^3}{\alpha^2} \cdot \frac{4}{9 e_Q^2}.$$

(Γ^h : strong interaction decay width, not taking into account the decay of V via a virtual photon into hadrons).

Recently it was pointed out⁵⁾ that also the decay $V_{\bar{Q}Q} \rightarrow \gamma + 2 \text{ gluons}$ could be calculated in the same way. One obtains:

$$\frac{\Gamma(V_{\bar{Q}Q} \rightarrow \gamma + 2 \text{ gluons})}{\Gamma^h(V_{\bar{Q}Q} \rightarrow 3 \text{ gluons})} \cong \frac{\Gamma(V_{\bar{Q}Q} \rightarrow \gamma + \text{hadrons})}{\Gamma^h(V_{\bar{Q}Q} \rightarrow \text{hadrons})} \quad (2)$$

$$= \frac{36}{5} \cdot e_Q^2 \cdot \frac{\alpha}{\kappa}.$$

In case of $e_Q = 2/3$ (e.g. charm, t-quark,...) the inclusive radiative rate is surprisingly big ($\approx 12\%$ for $\kappa \approx 0.2$) while in case of $e_Q = -1/3$ (e.g. b-quark) it is about 3 %.

Furthermore, one has

$$\frac{\Gamma(V_{\bar{Q}Q} \rightarrow \gamma + \text{hadrons})}{\Gamma(V_{\bar{Q}Q} \rightarrow e^+e^-)} = \frac{8}{9} \cdot \frac{(\pi^2-9)}{\pi} \cdot \frac{\kappa^2}{\alpha}. \quad (3)$$

The relations (1) and (3) can be combined to give a relation for the radiative inclusive decay rate, which is independent of κ :

$$\begin{aligned} \frac{\Gamma(V_{\bar{Q}Q} \rightarrow \gamma + \text{hadrons})}{\Gamma(V_{\bar{Q}Q} \rightarrow e^+e^-)} &= \left(\frac{\Gamma^h(V_{\bar{Q}Q} \rightarrow \text{hadrons})}{\Gamma(V_{\bar{Q}Q} \rightarrow e^+e^-)} \right)^{2/3} \\ &= \left(\frac{\pi^2-9}{\pi} \cdot \frac{3^2 \cdot 2}{5^2} \cdot \alpha \cdot e_Q^4 \right)^{1/3} \\ &= \left(\frac{\Gamma^h(V_{\bar{Q}Q} \rightarrow \text{hadrons})}{\Gamma(V_{\bar{Q}Q} \rightarrow e^+e^-)} \right)^{2/3} \cdot e_Q^{4/3} \cdot 0.45. \end{aligned} \quad (4)$$

The ratio eq.(4) is about 1.2 in case of the ψ (J) meson

($e_Q = e_c = 2/3$), i.e. the inclusive radiative decay rate is slightly larger than the leptonic annihilation rate.

3. Gluon jets and direct photons in $\bar{Q}Q$ -decay.

We suppose that besides the total hadronic annihilation rate also detailed properties of the final hadronic state can be abstracted from the lowest order QCD formula. In particular we conjecture that in case of very heavy $\bar{Q}Q$ vectormesons the final hadronic state consists of three jets, which originate from the initial production of three "massless" gluons (see Fig. (1a)). Momentum conservation requires that the three particle jets are coplanar in the restsystem of V .

As emphasized above, also the radiative decay $V_{\bar{Q}Q} \rightarrow \gamma + \text{hadrons}$ is quite important. In this case we expect one energetic photon to be produced together with two jets (see Fig. (1b)).

We denote the energies of the various "gluon jets" by E_i ($i=1, 2, 3$) and introduce the scaling variables $\xi_i = 2E_i/M_V$. The jet configuration (energies, angles) is determined uniquely if two of the energies E_i are given. Energy and momentum conservation require $E_i \leq M_V/2$ (or $\xi_i \leq 1$). The energy distributions are identical to the one obtained in ortho-positronium decay (see e.g. ref. (3)). One finds for the hadronic decay rate of a $(\bar{Q}Q)$ 1^{--} groundstate:

$$\frac{d^2\Gamma^h/d\xi_1 d\xi_2}{\Gamma^h} = \left[\left(\frac{1-\xi_3}{\xi_1 \xi_2} \right)^2 + \left(\frac{1-\xi_2}{\xi_1 \xi_3} \right)^2 + \left(\frac{1-\xi_1}{\xi_2 \xi_3} \right)^2 \right] \cdot \frac{1}{(\pi^2-9)}. \quad (5)$$

Integration over ξ_2 leads to the one jet energy distribution function

$$\frac{d\Gamma^h/d\xi}{\Gamma^h} = \frac{2}{(\pi^2-9)} F(\xi) \quad (6)$$

where $F(\xi)$ is given by

$$F(\xi) = \frac{\xi(1-\xi)}{(2-\xi)^2} + \frac{2-\xi}{\xi} + 2 \left(\frac{1-\xi}{\xi^2} - \frac{(1-\xi)^2}{(2-\xi)^3} \right) \ln(1-\xi). \quad (7)$$

The function $F(\xi)$, which is well-known from the analysis of positronium decay, increases monotonically from 0 at $\xi=0$ to 1 at $\xi=1$ (see Fig. (2)). The energy distribution of gluon jets can in principle be measured directly, for example by a calorimeter experi-

ment. We emphasize that the most probable case is $\xi = 1$, i.e. the case where a gluon jet carries the energy $M_V/2$.

The average energy of a gluon jet is given by

$$E_{av} = 1/2 M_V \cdot \xi_{av} = 1/2 M_V \cdot \int F(\xi) \cdot \xi d\xi / \int F(\xi) d\xi = \frac{1}{3} M_V.$$

Inclusive direct γ rays are expected to have the same energy spectrum as the gluon jets. One finds

$$\frac{d\Gamma(V_{QQ}^- \rightarrow \gamma + \text{hadrons}) / d\xi_\gamma}{\Gamma(V_{QQ}^- \rightarrow \gamma + \text{hadrons})} = \frac{2}{(\pi^2 - 9)} F(\xi_\gamma) \quad (8)$$

where we have used the scaling variable $\xi_\gamma = 2E_\gamma/M_V$.

We emphasize: It is important to look for inclusive γ -rays. For example in the decay of T (9.5) one expects to see γ -rays with an energy up to 4.75 GeV. The average energy of direct γ -rays is $M_V/3$.

4. Energy and angular distributions

We can describe the three gluon decay of V_{QQ}^- within a Dalitz plot which is symmetric with respect to the variables ξ_1, ξ_2, ξ_3

($\xi_1 + \xi_2 + \xi_3 = 2$). The variables ξ_i vary within the triangle, shown in Fig. (3), where also the ratio

$$\frac{d^2\Gamma^h/dS}{\Gamma^h} = |\text{decay amplitude}|^2$$

(dS : area element in triangle) is described. Note that the amplitude reaches its maximum at the three sides of the triangle, where one of the jet energies reaches its maximum $M_V/2$. The absolute value of the amplitude is uniform ($= \sqrt{2}$) for these configurations.

It is useful to consider the angles between the three jets, which we define as displayed in Fig. (4a). The configuration is described uniquely by the two angles θ, ϕ ; one finds:

$$\begin{aligned} \xi_1 &= \frac{2 \sin(\theta - \phi)}{A} \\ \xi_2 &= \frac{2 \sin \phi}{A} \\ \xi_3 &= \frac{-2 \sin \theta}{A} \end{aligned} \quad A = \sin \phi - \sin \theta + \sin(\theta - \phi).$$

Note the condition $0 < \theta < \pi$, $\pi < \phi < \pi + \theta$.

Probably it will be difficult in case of $T(9.5)$ to determine the various jet axes with good accuracy in the e^+e^- -annihilation experiments. Therefore we divide all events into two classes:

Events of type A:

We require that each jet axis can be arranged to lie within the shaded area of Fig. (4b), which describes all configurations, where the various jet axes deviate from the symmetric configuration $\xi_1 = 2/3$, $\theta = 120^\circ$, $\phi = 240^\circ$ by less than 20° ("Mercedes event"). These configurations obey the constraint that all angles between two neighbouring jets are more than 80° and less than 160° .

Events of type B: All other configurations.

In Fig. (5) we have indicated the areas of A and B type events. Events of type A are such that perhaps the genuine three jet structure could be observed in $T(9.5)$ decay, while the events of type B will resemble a two jet event. We have calculated the probability to obtain a type A event; 38 % of all events are expected to be of type A. Correspondingly 62 % of all events are of type B, where it will be difficult to observe the three jet structure.

Similar considerations can be applied to the decay $T \rightarrow \gamma +$ hadrons. The latter can also be illustrated by a Dalitz plot analogous to the one displayed in Fig. (3). We can also divide all events of the type $T \rightarrow \gamma +$ hadrons in events of type A and type B (see definition above). Radiative events of type A are such that one energetic photon and two distinct gluonic jets emerge; 38 % of all radiative decays are expected to be of type A. In radiative events of type B one photon and two gluon jets, which are nearly collinear, are emitted. A final state results consisting of a photon of nearly the mass $M_T/2 = 4.75$ GeV, and a hadronic system, carrying about the same energy, emitted into the opposite direction. 62 % of all radiative events are expected to be of this type.

What can one say about the structure of gluonic jets? In accordance with naive ideas about the fragmentation of colored constituents into color singlet hadrons one expects that particles which carry the corresponding constituent as a "valence constituent" are favored by the fragmentation process. Thus "glue ball states" should be favored by the fragmentation of gluon jets²⁾. Since "glue balls" must be rather heavy ($M > 1 \text{ GeV}$) and probably disintegrate into many hadrons, the hadrons produced in the fragmentation of a gluon will be rather soft. It will be difficult to observe the jet structures, unless one considers the hadronic decay of very heavy quarkonium states ($M > 15 \text{ GeV}$). In case of T (9.5) it seems promising to us to study the gluon jets by considering the radiative decays, where one of the three gluon jets is replaced by a photon of energy $> 3 \text{ GeV}$.

Within the QCD approach the mixing of the pseudoscalar mesons proceed via the two gluon annihilation term.^{2,6)} Therefore, one expects the η and η' meson to be preferred in the fragmentation of gluons. The leading particles in gluon jets might well be η and η' . We suggest to study in detail the inclusive η and η' -spectrum in heavy quarkonium decay.

Finally we should like to mention the hadronic decay of O^{-+} , O^{++} and 2^{++} quarkonium states. In case of the T spectroscopy such states will be produced in e^+e^- -annihilation by the radiative transitions $T \rightarrow (O^{-+}) + \gamma$ or $T' ("") \rightarrow (O^{++}, 2^{++}) + \gamma$. Their hadronic decays will proceed via the disintegration into a two gluon jet configuration. Provided the radiative transitions can be identified, e.g. by the detection of the emitted photon, it seems possible to study the two-jet structures in these decays in e^+e^- -annihilation experiments. It might be easier to see the two-jet structures in these decays than the three jet structures in case of 1^{--} -decay, since in the two-gluon decay both jets will carry an energy of nearly 5 GeV.

CONCLUSIONS

The hadronic decay of heavy quarkonium states seems an ideal tool to study gluon jets and the fragmentation of gluons into hadrons. We estimated that a relatively large portion of all decays of heavy 1^{--} quarkonium states are of the "Mercedes" type where the angle between two jet axes is more than 80° . Furthermore the radiative decays resulting in one energetic photon and two gluonic jets constitute a sizable fraction of quarkonium decays.

After this paper was essentially completed, we received a preprint by Koller and Walsh⁷⁾ in which ideas very similar to ours are discussed. One of us (H.F.) is indebted to H. Meyer for useful discussions.

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FIGURE CAPTIONS:

- Fig. 1 a: The decay of a heavy $\bar{Q}Q$ vectormeson into three gluons (g), leading to a three jet structure of the hadronic final state.
- Fig. 1 b: The decay of a heavy $\bar{Q}Q$ vectormeson into a direct photon (γ) and two gluons (g), leading to two jets of hadrons.
- Fig. 2: The function $F(\xi)$ which describes the energy distribution of the gluon jets.
- Fig. 3: Dalitz plot for the three gluon decay. The $|\text{decay amplitude}|^2$ is shown. The distances from each point inside the triangle to the three sides of the triangle are a measure of the scaling parameters ξ_1, ξ_2, ξ_3 . The normalization is such that one has $\xi_1 + \xi_2 + \xi_3 = 2$.
- Fig. 4 a: Definition of the angles θ and ϕ .
- Fig. 4 b: The shaded area defines the region where type A-events are located.
- Fig. 5: The distribution of type A and type B events in the three-gluon Dalitz plot.

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

Fig. 5