EXCLUDING SCALAR GLUONS

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We investigate the Dalitz plot population and thrust angular distribution for the orthoquarkonium decay $Q\bar{Q} \to$ three *scalar* gluons. The Dalitz plot for scalar gluons is populated in corners where events are two-jet-like and this disagrees with existing upsilon data. The scalar gluon thrust angular distribution is also in striking disagreement with the Υ data and so scalar gluons are completely ruled out.

Υ decays have been studied by three groups at the DORIS storage ring [1–3]. The most extensive analysis has been performed by the PLUTO group [4]. Perturbative QCD requires that Υ decays into three gluon jets. As a consequence of the relative low Υ mass these gluon jets will be rather broad and the analyses are in agreement with jets of mean half angle $\delta \gtrsim 30°$. So the jet character is not obvious to direct inspection and has to be resolved by a three-jet Monte Carlo method. This is done by looking at differential sphericity, thrust, triplicity, acoplanarity distributions, energy flow pattern, angular distributions relative to the beam, and distributions of angles between jets. All investigated distributions show agreement with the Υ decay into three *vector* gluons. There is disagreement with a pure $\Upsilon \to$ two-jet decay and with a simple phase space Monte Carlo model. One may conclude that the vector gluon model is correct. But we would like to have more direct evidence for certain aspects of the model. One aspect is the gluon quantum numbers.

In this letter we will report the main results of an investigation of the gluon spin in orthoquarkonium decays. In principle we will consider the five possibilities for the spin parity of the elementary gluon, according to the Dirac covariants $\mathbf{1}, \gamma_\mu, \gamma_5\gamma_\mu, \sigma_{\mu\nu}, \gamma_5$. The quark spin of the light quarks is 1/2, as proven experimentally by jet angular distributions [3,5]. So quarks are fermions. In the following we argue on physical grounds that gluons are either scalars or vectors:

If the charmonium or Υ binding forces were pure one gluon exchange, we could already rule out pseudoscalar, axialvector and tensor gluons [6]. The reason is that in the nonrelativistic limit pseudoscalar gluons do not bind fermion–antifermion at all, while axialvector or tensor gluons give a static potential proportional to the quark spins: attractive for spins aligned and repulsive for spins antiparallel or vice versa. Since we know bound quark–antiquark systems with spins aligned, like ρ, ϕ, J/Ψ, Υ, K^*, D^*, F^* etc. and systems with spins antiparallel, e.g. π, K, D, F, etc., this is ruled out. Unfortunately our argument is not tight, because the static confinement potential probably is a collective multi gluon effect. Thus it tells us little about the single gluon spin parity.

Single gluon exchange, however, governs short distance effects, which indeed seem to exclude $\gamma_5, \gamma_5\gamma_\mu, \sigma_{\mu\nu}$ gluons. Potential models for quarkonium [7] show a reasonable agreement with experiment. These potential models employ a static Coulomb-like short distance potential with small spin dependent corrections. As discussed before, this can only arise through scalar or vector gluon exchange. Thus gluons are either scalars or vectors.

It was shown recently that deep inelastic lepton hadron scattering experiments clearly favour vector over scalar gluons (and QCD over fixed point theories) [8]. However, it is welcome to have another, completely different, distinctive test on the nature of the gluon.

Of course, the only known candidate for a field theory of quarks and gluons, QCD, is a gauge theory and therefore demands the gluons to be vectors. This is the reason why nearly all calculations concerning gluon jets have assumed vector gluons. Only for the gluon bremsstrahlung process off hard quarks [9,10] and for quarkonium P wave decays [11,12] alternative calculations with scalar gluons have been performed. For the orthoquarkonium ground state decay, where experimental data are available, the scalar gluon calculation is presented here. The matrix element m for $Q\bar{Q} \to$ three vector gluons of momenta k_i, polarisations ϵ_i and colour λ_i is well known. To zeroth order in the quark velocities

$$m = \mathrm{Tr} \int \frac{\mathrm{d}^4 q}{(2\pi)^4}\, \psi(P, q) N_\mathrm{v}(\lambda_i, \epsilon_i, k_i; i = 1, 2, 3)\,, \quad (1)$$

where the Bethe–Salpeter amplitude ψ in its rest frame, $P = k_1 + k_2 + k_3 = (M, \mathbf{0})$, is in the zero binding limit, $M = 2m_\mathrm{Q}$,

$$\psi(M, q) = (2\pi/\mathrm{i})\, \delta(q_0) \sqrt{2M}\, u(\boldsymbol{q})\, \bar{v}(-\boldsymbol{q})\, \phi_\mathrm{nr}(\boldsymbol{q})\,, \quad (2)$$

with the Schrödinger wavefunction $\phi_\mathrm{nr}(\boldsymbol{r})$ normalized to 1 and (colour D coupling)

$$N_\mathrm{v}(\lambda_i, \epsilon_i, k_i) = 3^{-1/2} g^3\, \tfrac{1}{2}\mathrm{Tr}\left[\frac{\lambda_1}{2}\frac{\lambda_2}{2}\frac{\lambda_3}{2} + \frac{\lambda_1}{2}\frac{\lambda_3}{2}\frac{\lambda_2}{2}\right] \times \left\{ \not{\epsilon}_1 \frac{\not{P}/2 - \not{k}_1 + m_\mathrm{Q}}{P\cdot k_1} \not{\epsilon}_2 \frac{-\not{P}/2 + \not{k}_3 + m_\mathrm{Q}}{P\cdot k_3} \not{\epsilon}_3 + \text{all perm. } (1, 2, 3) \right\}. \quad (3)$$

In the scalar gluon case the minimal number of gluons in $^3\mathrm{S}_1$ $Q\bar{Q}$ annihilations is three, again, as in the vector gluon case [‡1]. Three coloured gluons are necessary to construct a C-odd colour singlet. Thus the matrix element for $Q\bar{Q} \to$ three scalar gluons is again given by eq. (1), replacing $N_\mathrm{v}(\lambda_i, \epsilon_i, k_i)$ by

$$N_\mathrm{s}(\lambda_i, k_i) = 3^{-1/2} g^3\, \tfrac{1}{2}\mathrm{Tr}\left[\frac{\lambda_1}{2}\frac{\lambda_2}{2}\frac{\lambda_3}{2} - \frac{\lambda_1}{2}\frac{\lambda_3}{2}\frac{\lambda_2}{2}\right] \times \left\{ \frac{\not{P}/2 - \not{k}_1 + m_\mathrm{Q}}{P\cdot k_1} \frac{-\not{P}/2 + \not{k}_3 + m_\mathrm{Q}}{P\cdot k_3} + \text{even perm. } (1, 2, 3) - \text{odd perm. } (1, 2, 3) \right\}. \quad (4)$$

where the scalar gluons appear in colour F coupling. The antisymmetry of the F coupling excludes all further diagrams where two or three scalar gluons attach to the same vertex.

Evaluating and squaring the matrix element eq. (1) and summing over gluon polarizations in the vector gluon case leads to the decay width of the form $\mathrm{d}\Gamma \sim L_{\mu\nu} H^{\mu\nu}$, where $L_{\mu\nu} = \epsilon_\mu \epsilon_\nu^*$, ϵ being the $Q\bar{Q}$ (or virtual photon) polarization vector. The hadronic tensor, $H^{\mu\nu}$, takes the form, $(x_0, \boldsymbol{x})_i \equiv 2(k_0, \boldsymbol{k})_i/M$, $x_i \equiv x_{0i} = |\boldsymbol{x}_i|$, $x_1 + x_2 + x_3 = 2$,

$$H_\mathrm{v}^{\mu\nu} = (1/x_1^2 x_2^2 x_3^2) \times \{g^{\mu\nu}[x_1^2(1 - x_1)^2 + x_2^2(1 - x_2)^2 + x_3^2(1 - x_3)^2] + k_1^\mu k_1^\nu[(1 - x_1)^2 + (1 - x_3)^2] + k_2^\mu k_2^\nu[(1 - x_2)^2 + (1 - x_3)^2] + 2k_1^\mu k_2^\nu (1 - x_3)^2\}\,, \quad (5)$$

in the vector gluon case. In the scalar gluon case it is simply the square of a vector,

$$H_s^{\mu\nu} = z^\mu z^{\nu *}\,, \quad z^\mu = \frac{(3x_2 - 2)k_1^\mu - (3x_1 - 2)k_2^\mu}{4x_1 x_2 x_3}. \quad (6)$$

Summing over the ϵ polarisation gives the Ore–Powell formula $(x_1 > x_2 > x_3)$

$$\Gamma_\mathrm{v}^{-1}\mathrm{d}\Gamma_\mathrm{v}/\mathrm{d}x_1\mathrm{d}x_2 = [6/(\pi^2 - 9)]\, [x_1^2(1 - x_1)^2 + x_2^2(1 - x_2)^2 + x_3^2(1 - x_3)^2]/x_1^2 x_2^2 x_3^2\,, \quad (7)$$

for the vector gluon case and $(x_1 > x_2 > x_3)$

$$\Gamma_\mathrm{s}^{-1}\mathrm{d}\Gamma_\mathrm{s}/\mathrm{d}x_1\mathrm{d}x_2 = (\ln M/\Delta)^{-1} \times [(x_1 - x_2)(x_3 - x_2)(x_1 + x_3 - x_2) + \text{even perm. } (1, 2, 3)]/x_1^2 x_2^2 x_3^2\,, \quad (8)$$

for the scalar gluon case. The Dalitz plot populations (7) and (8) are shown in fig. 1. They demonstrate the strong gluon spin dependence. While for vector gluons

‡1 Here we assume that the scalar gluons are colour octets just as vector gluons. If the scalar gluons were colour singlets the two gluon decay of the $^3\mathrm{S}_1$ $Q\bar{Q}$ state is forbidden by Bose symmetry. So the decay proceeds via three gluons. Anyway, if the $^3\mathrm{S}_1$ $Q\bar{Q}$ state would decay into two spinless quanta, our results, the two jet topology and jet axis angular distribution, would follow trivially

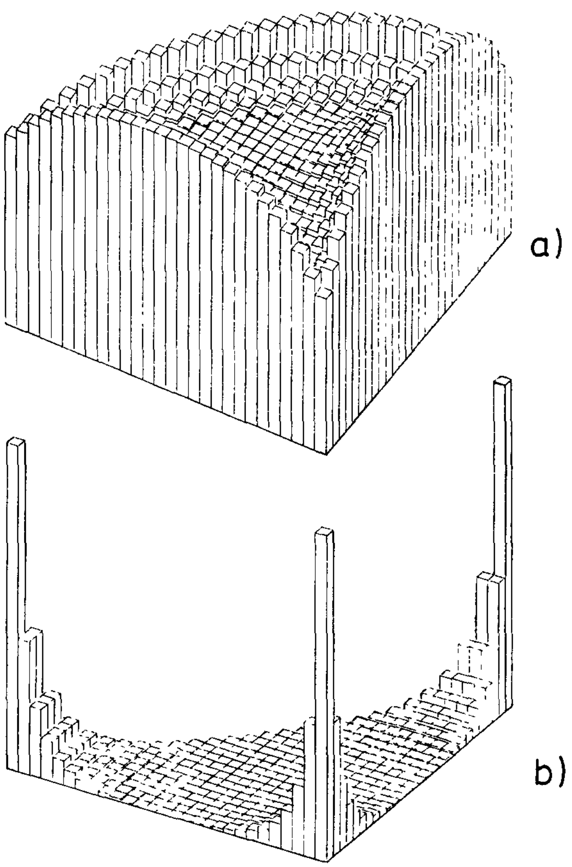

Fig. 1. The Dalitz plot population of $^3S_1$ $Q\bar{Q} \to 3g$ for (a) vector gluons and (b) scalar gluons.

the Dalitz plot is uniformly populated, for scalar gluons it has singular peaks in the corners and zeros at the center as well as in the middle of each boundary line.

The angular distributions are given by

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta\ \mathrm{d}T} \sim [(1+\cos^2\theta)\sigma_U(T) + 2\sin^2\theta\sigma_L(T)]$$

$$\equiv (\sigma_U(T) + 2\sigma_L(T))(1+\alpha(T)\cos^2\theta)\,, \qquad (9)$$

where

$$\sigma_U \sim H^{11} + H^{22}\,, \quad \sigma_L \sim H^{33}\,, \qquad (10)$$

and $H^{\mu\nu}$ is taken from eq. (5) or (6), respectively. θ is the angle between the most energetic gluon ($\boldsymbol{x}_1$) and the beam axis. For the vector gluon case $\sigma_U(T)$ and $\sigma_L(T)$,

$$\sigma(T) = \sigma(x_1) = \int\limits_{x_1>x_2>x_3} \mathrm{d}x_2\,\sigma(x_1,x_2)\,,$$

are given in ref. [14] and for the scalar gluon case we obtain

$$\sigma_U(T) = \frac{(1-T)(2-3T)^2}{3T^4(2-T)^2} \times \left[\frac{2-3T}{T} + \frac{2T^2-4T+4}{2-T}\ln\frac{T}{2(1-T)}\right], \qquad (11)$$

$$\sigma_L(T) = -\frac{(1-2T)^2}{3T^4} \times \left[\frac{2-3T}{T(1-T)} + \frac{4}{2-T}\ln\frac{T}{2(1-T)}\right]. \qquad (12)$$

Summing eqs. (11) and (12) yields $\mathrm{d}\Gamma/\mathrm{d}T$ which is plotted in fig. 2 together with the well known vector gluon result [11,13,14]. $\mathrm{d}\Gamma/\mathrm{d}T$ demonstrates again what can be seen in the Dalitz plot: quarkonium decays into scalar gluons all look like genuine two jet events. They all result in two hard and one extremely soft quanta.

Much more important for the determination of the gluon spin are of course angular distributions. The thrust angular distribution is characterized by

$$\alpha(T) = (\sigma_U - 2\sigma_L)/(\sigma_U + 2\sigma_L)$$

in eq. (9). A simple helicity argument requires that in the limit $T \to 1$ $\alpha(T)$ approaches +1 for vector gluons and −1 for scalar gluons. A measurement of $\alpha(T)$ over the entire T range is most interesting. However, at present the broad gluon fragmentation and limited

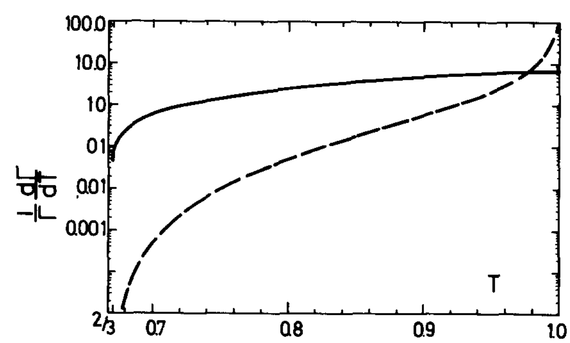

Fig. 2. $(1/\Gamma)\mathrm{d}\Gamma/\mathrm{d}T$ for vector gluons (full line) and scalar gluons (dotted line).

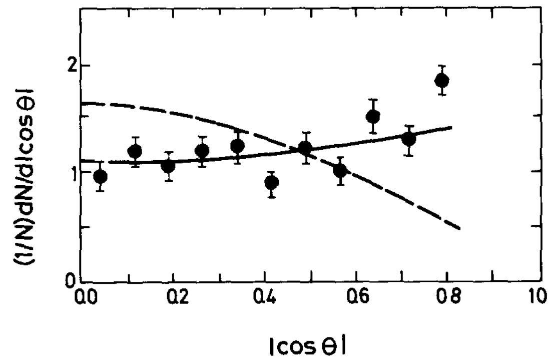

Fig. 3. The jet axis angular distribution as measured by PLUTO and the theoretical (normalized) curves for vector gluons (full line) and scalar gluons (dotted line).

statistics do not allow a measurement of the shape of $\alpha(T)$ [‡2], but only of its mean value. The average $\langle\alpha(T)\rangle$ is obtained by just summing over all events and therefore it is only affected by uncertainties in the determination of the thrust axis. QCD (vector gluons) predicts $\langle\alpha(T)\rangle = 0.39$ [14]. Calculating $\langle\alpha(T)\rangle$ for scalar gluons means, roughly, to weight every value of $\alpha(T)$ with $\mathrm{d}\Gamma/\mathrm{d}T$ of fig. 2, which is singular for $T \to 1$, i.e. the average is very close to $\alpha(T=1) = -1$. We find

$$\langle\alpha(T)\rangle = -0.995 ,$$

for scalar gluons [‡3]. This is a drastic difference in the thrust axis angular distribution between vector and scalar gluons. We compare both predictions in fig. 3 with the Υ angular distribution as measured by PLUTO. A fit to the data points gives the coefficient of the $\cos^2\theta$ term [‡4] to be $+0.83 \pm 0.23$ [4]. It is obvious that this angular distribution is incompatible with spin zero gluons.

We conclude that, based on the Dalitz plot and jet axis angular distribution, scalar gluons are ruled out by the Υ data.

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‡2 We are confident that a measurement of the function $\alpha(T)$ will be much easier at the $t\bar{t}$ resonance.

‡3 This calculation will be described more detailed in a future publication.

‡4 PLUTO [4] has measured the coefficient α in the $1 + \alpha\cos^2\theta$ distribution of the charged sphericity axis only. Including neutrals (and using thrust) should improve the measurement. But note that the sphericity and thrust axis to which $\langle\alpha(T)\rangle$ corresponds lie very close to each other.

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