THE STUDY OF GLUEBALL — Υ AS A GLUEBALL FACTORY

S.-H. Henry Tye
Laboratory of Nuclear Studies
Cornell University
Ithaca, NY 14853

QCD predicts the existence of gluons which couple among themselves as well as to quarks. The gluon self-coupling is what qualitatively differentiates them from the photon. Hence it is crucial to establish the existence of gluons and their mutual interactions. There are many indirect tests of QCD (such as scaling violation in deep-inelastic scatterings), whose experimental results are very encouraging. However, it is essential to prove the existence of their self-couplings via tests that are more direct. Because of confinement, we do not expect to see free gluons propagating in space. In the absence of free gluons, the best places to look for their existence and self-couplings are probably the following:

(1) gluon jets: this has been observed in PETRA. However, its properties remain to be studied in detail. In particular, the $p_\perp$ spread of the gluon jets (for large $p_\perp$ and energetic gluon jets) provides a measurement of the triple-gluon vertex(1).

(2) Vibrational states(2) in quarkonia: In the string picture, these are states with the string in some vibrational modes; in the bag model, these are bags with non-trivial gluonic modes in addition to the quark-antiquark pair. It is believed that such states are responsible for the high degeneracy of states in the light meson system. So far, these additional states remain to be seen in the Υ spectroscopy while there are candidates in the 4.0 GeV region in the ψ spectroscopy. The theoretical status of these vibrational states remains to be understood.

(3) Glueball (or gluonium) states, which we shall discuss in some detail later.

Of the above three, gluon jets reflect most explicitly the gluonic degrees of freedom as one expects in perturbative QCD. The best place to test this property is where gluon jets are produced back-to-back. The decays of the (0^{++}), (2^{++}) P states and the pseudoscalar η_b in the Υ spectroscopy are ideal sources for back-to-back gluon jets. On the other hand, vibrational states originate from some coherent gluonic effects resulting from the confinement mechanism in non-perturbative QCD. Thus gluon jets and vibrational states are two totally different manifestations of the gluonic degrees of freedom, much like the two sides of the same coin. Properties of these additional states in the Υ spectroscopy are not well understood. Hence experimental input on their existence or absence and on their properties, if they exist, will be most valuable.

Gluoniums are bound states of gluons.(3) Their existence is possible because of the gluon self-coupling. They should exist in perturbative QCD as well as in the strong coupling domain of QCD. Such states may have been observed at SPEAR already.(4) It would be interesting to observe them at CESR, using the same radiative transition,

$$\psi/J,\ \Upsilon \to \gamma + G$$

where G is a glueball with the appropriate quantum number. Chanowitz has given a detailed discussion of this(5)

For the Υ system, the branching ratio of $\Upsilon\to\gamma G$ is suppressed because of the b quark charge and the kinematic factors of this exclusive process

$$\frac{\Gamma(\Upsilon\to\gamma G)}{\Gamma(\psi\to\gamma G)} \simeq \left(\frac{Q_b}{Q_c}\right)^2 \frac{M_\psi^2}{M_\Upsilon^2} \simeq \frac{1}{40}$$

This gives a branching ratio of

$$B(\Upsilon\to\gamma G)\ B(G\to K\bar{K}\pi) \sim 10^{-4}$$

as compared to the case for

$$B(\psi\to\gamma G)\ B(G\to K\bar{K}\pi) \sim 4\times 10^{-3}$$

if we assume the ι(1440) to be a glueball. With a super luminosity e^+e^- machine ($\sim 10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$)(6), we expect 200 million Υ's from one year's (ie. 10^7sec/yr.) running. Hence we can expect 20K events with $K\bar{K}\pi$ decay product from the ι(1440) produced via the radiative decay of the Υ. In fact, glueballs produced via $\Upsilon\to\gamma G$ can have the following quantum numbers: $G(0^{++})$, $G(2^{++})$, $G(0^{-+})$, $G(1^{-+})$, $G(2^{-+})$... etc. The low multiplicity and the hard photon provide a very distinct signal for detection. The expected event rates should provide a clean study of the various properties of the glueballs. It is clear that for glueball masses smaller than 3 GeV, ψ provides a more powerful factory for glueball production. For glueballs with masses above 3 GeV, the Υ factory is needed.

In addition, glueballs can be produced via Υ decay in a number of other ways. This means Υ decay may produce gluonium states that cannot be reached via ψ/J decay. Because Υ and ψ/J are 1^{--} states, radiative transition can only produce gluonium states with the appropriate quantum numbers (0^{-+}, 0^{++}, 2^{++} etc.). The Υ state, on the other hand, can decay via(7)

$$\Upsilon \to G_1 + G_2$$

where G_1 and G_2 are two different gluonium states. This is a two-body decay mode and should have some distinct signals. Since gluonium states have masses ~1.4-2.0 GeV, such a decay mode is not feasible at ψ/J. This decay mode can reach many gluonium states:

S- and D-wave allowed decays

$$\begin{aligned}\Upsilon\to\ & G(0^{++})\ G(1^{--})\\ & G(2^{++})\ G(1^{--})\\ & G(0^{-+})\ G(1^{+-})\\ & G(1^{-+})\ G(1^{+-})\\ & G(2^{-+})\ G(1^{+-})\end{aligned}$$

etc.

P-wave allowed decays

$$\begin{aligned}\Upsilon\to\ & G(0^{-+})\ G(1^{--})\\ & G(1^{-+})\ G(1^{--})\\ & G(2^{-+})\ G(1^{--})\\ & G(0^{++})\ G(1^{+-})\\ & G(2^{++})\ G(1^{+-})\end{aligned}$$

etc.

A dimensional argument gives

$$\frac{\Gamma(\Upsilon \to G_1 G_2)}{\Gamma(\Upsilon \to 3 \text{ gluons})} \sim \alpha_s^2 \frac{m_G^2}{M_\Upsilon^2} \left(\frac{f_1}{m_{G_1}}\right)^2 \left(\frac{f_2}{m_{G_2}}\right)^2$$

$$\sim 10^{-3} \left(\frac{f_1}{m_{G_1}}\right)^2 \left(\frac{f_2}{m_{G_2}}\right)^2$$

where we take the glueball masses to be $m_{G_1} \simeq m_{G_2} \simeq 1.5$ GeV, and f_1, f_2 are the glueball decay constants of the glueballs G_1 and G_2 respectively. The two powers of α_s is due to the fact that an odd charge conjugation ($c = -1$) glueball must have 3 or more gluons in the perturbative picture[8].

Clearly the decay width of $\Upsilon \to G_1 G_2$ is very sensitive to the glueball decay constants.

The glueball decay constant is a function of the glueball mass or $\Lambda_{\overline{MS}}$. It is reasonable to expect f to be of the order of a few hundred MeV. For $f \gtrsim 0.5$ GeV[9], we have B.R.$(\Upsilon \to G_1 G_2) \sim 10^{-5}$. This will give, e.g., 2000 events of $\Upsilon \to G(0^{++})\, G(0^{-+})$ in one year's running on the Υ in the super luminosity machine. Since the even conjugation glueballs should have been well studied via $\psi, \Upsilon \to \gamma G(J^{P+})$, information on $G(J^{P+})$ should facilitate the study of the odd conjugation glueballs.

The signal for $\Upsilon \to G_1 G_2$ should be quite distinct. The glueball decays into two or three-body final states. So the resulting multiplicity of

$$\eta(\Upsilon \to G_1 G_2) \simeq 4 \sim 7$$

which is substantially lower than the average multiplicity of Υ decay into hadrons. Also, the momentum of the glueball is $\gtrsim 4.0$ GeV so that the x distribution of the hadrons from $\Upsilon \to G_1 G_2$ decay does not peak at small x. In fact, the distribution is suppressed at small x. This feature should differentiate it from normal hadronic decays of Υ.

Of course, glueballs can also be produced from decay in a number of ways:

$$\begin{aligned} \Upsilon &\to G_1 + \text{gluon jet} \\ &\to G_1 \eta,\ G_1 \pi\pi \\ &\to G_1 G_2 \pi\pi \\ &\to G_1 G_2 \eta \\ &\quad \text{etc.} \end{aligned}$$

The inclusive glueball decay modes $\Upsilon \to G_1 X$ are not suppressed by the kinematic factors that appear in exclusive decay modes. Hence we expect $\Upsilon \to GX$ to have a branching ratio of the order of a few percent or more. The difficulty is to reconstruct the glueballs from its decay product. With a large sample of Υ events and with a good detector, this task should be within reach.

The study of glueballs at ψ has been established as a promising avenue. The feasibility and the usefulness of the study of glueballs at Υ remains to be seen. Because of the rich (and not completely understood) meson spectroscopy, the possible existence of multiquark states, and the mixing of glueballs and meson states, the identification of glueball states and the analysis of their properties will be highly nontrivial. Therefore, it is important to have as many handles as one can get on the properties of glueballs. In this respect, the Υ factory can be very important, since it offers a number of different glueball production mechanisms.

Recent theoretical developments in QCD enable us to begin to study the glueball spectroscopy[10]. Using Monte Carlo methods on lattice gauge theory, glueball masses can be calculated in terms of the QCD scale parameter. In view of this, it is clear that experimental information on the glueball spectroscopy is being urgently sought after.

Discussions with Michael Chanowitz, Peter Lepage and Kyriakos Tsokos are valuable.

References

1. K. Shizuya and S.-H. H. Tye, Phys. Rev. Lett. 41, 787; 41 1195(E) (1978); Phys. Rev. D20, 1101 (1979) M. B. Einhorn and B. Weeks, Nucl. Phys. B146, 445 (1978).

2. See, e.g. W. Buchmuller and S.-H. H. Tye, Phys. Rev. Lett. 44, 850 (1980); P. Hasenfratz, R. R. Horgan, J. Kuti and J. M. Richard, Phys. Lett. 95B, 299 (1980).

3. For discussions of glueballs, see e.g. J. D. Bjorken, in Proceedings of SLAC Summer Institute on Particle Physics, 1979 edited by M. C. Zipf (1979); K. Koller and T. Walsh, Nucl. Phys. B140, 449 (1978); J. Coyne, P. Fishbane and S. Meshkov, Phys. Lett. 91B, 259 (1980); K. Johnson and C. B. Thorn, Phys. Rev. D13, 1934 (1976); R. L. Jaffe and K. Johnson, Phys. Lett. 60B, 201 (1976); P. Freund and Y. Nambu, Phys. Rev. Lett., 34, 1645 (1975). J.L. Rosner, Phys. Rev. D24, 1354 (1981).

4. For a review, see D. L. Sharre, in Proceedings of the 1981 International Symposium on Lepton and Photon Interactions at High Energies, edited by W. Pfeil (1981).

5. M. Chanowitz, this proceeding, and Phys. Rev. Lett. 46, 981 (1981).

6. M. Tigner, Cornell University Report, CBN 82-24 (1982); M. Tuts, this proceeding.

7. S.-H. H. Tye, Cornell University Report, CBX 80-69 (1980).

8. See, e.g. J. D. Bjorken, ref. 3, D. Robson, Nucl. Phys. B130, 328 (1977).

9. K. Tsokos (private communication.)

10. For a review, see e.g. P. Hasenfratz, in Proceedings of the 1981 International Symposium on Lepton and Photon Interactions at High Energies, edited by W. Pfeil (1981); C. Rebbi, Talk at the XXI International Conference at Paris (July 1982).