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Axigluons in the Υ system

M. A. Doncheski, H. Grotch, and R. W. Robinett
Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802
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We consider the virtual effects of axigluons, octet gauge bosons present in chiral-color models, in the Υ system. Specifically, we examine the decay $\Upsilon \rightarrow A^* g \rightarrow q\bar{q}g$, where A^* is a virtual axigluon, and the resulting contribution to the Υ hadronic width, and set the limit $M_A > 25$ GeV.

Recently proposed chiral-color models,[1] schemes where the strong-interaction gauge group above $\approx G_F^{-1/2} \simeq 250$ GeV is given by $SU(3)_L \times SU(3)_R$, imply a plethora of new strongly interacting particles near or below that scale. One model-independent prediction of these schemes is the existence of a massive octet of gauge bosons, the axigluons (A), which are remnants of the broken axial $SU(3)_A$ that results when the $SU(3)_L \times SU(3)_R$ symmetry is spontaneously broken, leaving only the familiar vector $SU(3)_c$ of color unbroken. These bosons, which couple as axial vectors to the familiar quarks, are often assumed to interact with the standard strong coupling constant and to have masses not much larger than the weak scale, and possibly (much?) smaller.

The natural place to look for such (presumably) heavy, strongly interacting particles is in hadronic collisions, and Bagger, Schmidt, and King[2] have surveyed the CERN (UA1) data, especially the single-jet inclusive cross section, and exclude axigluons in the mass range 125–250 GeV. They argue that the CERN collider should eventually be able to probe axigluon masses in the range between 100 and 300 GeV (and possibly light axigluons with masses between 20 and 50 GeV as well) while the Fermilab Tevatron and the Superconducting Super Collider will be able to search for even heavier masses. This still leaves open the possibility of relatively light axigluons which could be produced in e^+e^- collisions, and two papers have recently considered this possibility. Rizzo[3] has examined the decay $Z^0 \rightarrow q\bar{q}A$ where the axigluon is radiated from the final-state quark while Carlson, Glashow, and Jenkins[4] computed the rate for $Z^0 \rightarrow Ag$ which proceeds via loop diagrams (with contributions from either standard quarks or the additional exotic fermions present in typical chiral-color models).

Two groups[5,6] have also noted that because of the axial-vector couplings of the A to quarks (and its resulting charge-conjugation quantum number, $C = +1$, compared to $C = -1$ for gluons) the decays $V_q \rightarrow Ag$ [where $V_q = {}^3S_1(q\bar{q})$ is a vector quarkonium state] are also allowed (if kinematically accessible). Because this decay only involves two powers of α_s as compared to the standard three-gluon decay of a ${}^3S_1$ state, it can easily dominate the hadronic decays of sufficiently heavy quarkonia and can be used to exclude axigluon masses almost up to $M(V_q)$. The authors of Ref. 6, for example, find the ratio

$$\frac{\Gamma(V_q \rightarrow Ag)}{\Gamma(V_q \rightarrow 3g)} = \frac{18\pi}{5\alpha_s(\pi^2-9)}(1-r)(1+1/r) \qquad (1)$$

[where $r \equiv (M_A/M_V)^2$], and the numerical factor is seen to be almost exactly 100. [A similarly large ratio is familiar from the hadronic decays of the η_c (a ${}^1S_0$ state which can decay into two gluons) and the J/ψ.] The observed good agreement of Υ decays with theory then immediately implies that $M_A \gtrsim 10$ GeV. (The discovery of toponium resonances with standard hadronic widths would then, of course, extend this bound.) Because of the large numerical factor in Eq. (1), one can imagine that the axigluon could be reasonably off shell and still contribute an unacceptably large amount to the hadronic width of the Υ and thereby provide a more stringent limit on M_A. For this reason we are led to consider the decays $V_q \rightarrow A^* g \rightarrow q\bar{q}g$, where A^* is a virtual axigluon and we sum over the n quark pairs that are kinematically accessible (i.e., for Υ decay we consider $q = u,d,s,c$ so that $n = 4$).

The decay rate for this process is easily calculated using standard techniques for the annihilation decays of quarkonium systems,[7] the required integrals over the three-body phase space are easily done using standard techniques,[8] and the color factors can be checked from an earlier work involving decays with $q\bar{q}g$ final states.[9] The result for the decay rate is

$$\Gamma(V \rightarrow q\bar{q}g) = \frac{2^8 n\alpha_s^3 |\phi(0)|^2 M_V^2}{3^5 \pi M_A^4} F(x) \;, \qquad (2)$$

where n is the number of light quarks (here 4), $x=(M_A/M_V)^2$ and $F(x)=\frac{3}{2}x^2\{2x\ln[x/(x-1)]-2-1/x\}$. (We have assumed that the final quarks are massless.) The function $F(x)$ is normalized so that $F(x\to\infty)=1$ while it diverges for $x\to 1$ indicating the possibility of decays into real axigluons. If we compare this with the expression for the standard three-gluon decay,

$$\Gamma(V_q\to ggg)=\frac{40}{81}\frac{(\pi^2-9)}{\pi}\alpha_s^3\frac{|\phi(0)|^2}{M_V^2}\ , \tag{3}$$

we find the ratio

$$R=\frac{\Gamma(V\to q\bar{q}g)}{\Gamma(V\to ggg)}=\frac{128F(x)}{15(\pi^2-9)x^2}\ . \tag{4}$$

In order to set a limit on M_A we must consider the present theoretical understanding of hadronic decays of the Υ, especially the 1S state. The tree-level prediction for the three-gluon decay in Eq. (3) is subject to a large QCD correction factor (Ref. 10), $(1+3.8\alpha_s/\pi)$, and if we use $\alpha_s(M_\Upsilon^2)=0.2$ we find that this gives an increase of 1.25. Hadronic decays from quarkonium annihilations via a virtual photon, $\Upsilon\to\gamma^*\to q\bar{q}$, are also present at a rate about one-eighth that of the $3g$ decay which increases the hadronic width by another factor of ≈ 1.12. Keeping this in mind, we then insist, somewhat arbitrarily, that any contribution to the hadronic width from virtual-axigluon-induced decays not exceed the increase caused by the larger of these two factors, namely, the QCD corrections; i.e., we demand that $R<0.25$. (Since the resulting limit on M_A depends only on $R^{-1/4}$ it is only mildly dependent on our assumptions.) Using this constraint and the explicit form for $F(x)$, we find the bound $\sqrt{x}>2.6$ or $M_A>(2.6)M_\Upsilon=25$ GeV which increases the lower limit on M_A by a factor of 2.5 compared to the direct-axigluon-decay limit derived in Refs. 5 and 6. (If, for example, we insist instead that $R<0.5$ the limit is changed to $\sqrt{x}>2.2$ or $M_A>21$ GeV.) This method can then also be used to extend the range of axigluon masses probed by toponium resonances given sufficiently precise information on their hadronic decay widths. (Even if we only insist that $R<2$, i.e., the toponium hadronic width is known to a factor of 3, we still find that $\sqrt{x}>1.6$ or $M_A>1.6M_V$.) We have also examined the additional contributions to the fine-structure splitting in the Υ system (i.e., the P-state splittings) due to axigluon exchange and find that any limits derived from insisting that such splittings not be too large are significantly weaker than those we derive above.

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