PHYSICAL REVIEW D VOLUME 26, NUMBER 1 1 JULY 1982

Pair production of colored hypermesons at very high energy

J. A. Grifols and A. Méndez
Departament de Física Teòrica, Universitat Autònoma de Barcelona, Bellaterra, Barcelona, Spain
(Received 23 October 1981)

In the framework of current dynamical-symmetry-breaking models we study the pair production of colored pseudo-Goldstone bosons in future very-high-energy experiments. We compare pair production with single production through the anomaly-dominated gluon-gluon and photon-gluon fusion mechanisms.

Hypercolor[1] constitutes an extremely attractive framework for the implementation of dynamical symmetry breaking.[2] Indeed, it provides a natural scenario for the understanding of the generation of Z- and W-boson masses in exactly the ratio predicted by the standard electroweak model, $(M_Z/M_W)\cos\theta_W = 1+O(\alpha)$, and for solving the mass-hierarchy problem in grand unified theories (GUT's). Moreover, it avoids the high degree of arbitrariness introduced through Yukawa couplings of fermions to conventional fundamental scalar Higgs fields and provides a natural mechanism for implementing CP violation.[3] Despite these obvious successes a realistic realization of the hypercolor program is still lacking. There is an absolutely unavoidable feature, however, that any realistic model must possess. Namely, the existence of pseudo-Goldstone bosons (PGB's) with masses well below the typical mass scale of hypercolor forces ($\sim$1 TeV). So, independently of whichever the ultimate model of dynamical symmetry breaking might be, it must accommodate a set of relatively light mesons. These states (PGB's) supply a phenomenological handle on the hypercolor program since they might be detected in future accelerator experiments. In fact, there have been already many calculations and estimates of PGB production rates[4–8] both in e^+e^- and in hadron-hadron machines. Of course, elementary Higgs scalars can also be produced in those experiments and it is therefore of foremost importance to phenomenologically discriminate between both alternatives.

For the sake of definiteness we shall refer to the "one-family model" as given, e.g., in Ref. 2. This is not a restriction, since the gross properties of PGB's which we shall be concerned with should be shared by all models. These PGB's fall into two main categories. On one hand, there are color-singlet bosons $(P^{\pm},P^{0,3})$ which are very light ($\lesssim$8 GeV) compared to typical hyperhadron masses. We shall not consider them in what follows but refer, instead, to the already existing literature.[4,5] On the other hand, there are colored PGB's. Among the latter one finds color-triplet states $(P_3^{\pm,0,3},\bar{P}_3^{\pm,0,3})$, called leptoquarks, which have a mass of about 150 GeV, and also color-octet states $(P_8^{\pm},P_8^{0,3})$ which are somewhat heavier ($\sim$250 GeV). The bulk of the mass of the colored PGB's arises from one-gluon-exchange interactions[9] and depends on the scale $\Lambda_{\rm HC}$ of hypercolor interactions, the value of the QCD running coupling constant $g_s(E=\Lambda_{\rm HC})$ and color group-theory factors, and it is essentially independent of other details of the specific model.

The electrically neutral PGB octets, P_8^0 and P_8^3, can be *singly* produced through the anomaly-dominated fusion of gauge bosons, i.e., through gluon-gluon fusion in hadron-hadron machines and photon-gluon fusion in ep machines. The production cross sections[6–8] for different experiments are summarized in Table I. This production mechanism is interesting since Higgs bosons do not share an analogous coupling at the tree[10] level and therefore this process discriminates between the two alternative symmetry-breaking mechanisms. Unfortunately, the QCD background to these processes is severe. Nevertheless, a peak rises above background in the case of P_8^0 production in $(p\bar{p})$ collisions.[7]

In this paper we shall mainly concentrate on an alternative production process, namely, pairwise creation of colored PGB's by hadron-hadron collisions at very high energies like those to be reached at ISABELLE and the Fermilab collider, and by electron-proton collisions at HERA energies. As we shall argue later on, here background is less severe than in single-hypercolor-particle production.

Production of a pair of colored PGB's proceeds via gluon-gluon collisions and via quark-antiquark annihilations. The corresponding diagrams are shown in Fig. 1. The PGB's are minimally coupled to the gluons and, at the energies considered here, we do not expect these couplings of gluons to PGB's to deviate too much from pointlike structure. The Feynman rules of "scalar QCD" necessary for the evaluation of PGB production amplitudes are given in, e.g., Ref. 11. The cross section for the subprocess gluon + gluon $\rightarrow$ pair of PGB's involves a somewhat lengthy but straightforward calculation. After averag-

TABLE I. Cross sections for inclusive production of single neutral color-octet PGB's.

Facility	Process	Subprocess	$\sigma_{P_8^0}$ (cm^2)	$\sigma_{P_8^3}$ (cm^2)
HERA $\sqrt{s}\sim 335$ GeV	$\gamma p \to P_8 X$	$\gamma g \to P_8$	2×10^{-37}	2×10^{-36}
CERN SPS collider $\sqrt{s}\sim 500$ GeV	$p\bar{p} \to P_8 X$	$gg \to P_8$	1.7×10^{-37}	...
ISABELLE $\sqrt{s}\sim 800$ GeV	$pp \to P_8 X$	$gg \to P_8$	3.0×10^{-36}	...
Fermilab collider $\sqrt{s}\sim 2000$ GeV	$p\bar{p} \to P_8 X$	$gg \to P_8$	6.6×10^{-35}	...

ing and summing over initial and final colors, respectively, it reads

$$\sigma(gg \to P\bar{P}) = \frac{\pi\alpha_s^2(M)}{M^2}\frac{1}{2x^6}\{(\alpha x^2+\beta)x(x^2-1)^{1/2} - (2\gamma x^2 - \delta)\ln[x+(x^2-1)^{1/2}]\} , \tag{1}$$

where $x \equiv \sqrt{s}/2M$, M being the PGB mass and s the invariant mass squared of the $P\bar{P}$ system. The coefficients α, β, γ, and δ, which would be 1 in "Abelian QCD," are given in Table II.

The cross section due to $q\bar{q}$ annihilation is readily evaluated to be

$$\sigma(q\bar{q} \to P\bar{P}) = \frac{\pi\alpha_s^2(M)}{M^2}\rho\frac{(x^2-1)^{3/2}}{12x^5} , \tag{2}$$

where again ρ is to be taken from Table II.

To obtain the the physical cross section for $P\bar{P}$ production in pp or $p\bar{p}$ collisions we still have to convolute the above cross sections with the gluon distribution function in the proton (antiproton) in the first case, and with the quark and antiquark distribution functions in the proton (or antiproton) in the second case. To this end we took simple scale-invariant parametrizations for the quark and antiquark distribution functions and $G(\xi) = 3[(1-\xi)^5/\xi]$ for the gluon distribution function.

In planned future photoproduction experiments there is only phase space for $P_3^{\pm}\bar{P}_3^{\pm}$ production. The diagrams involved are those of Fig. 1(a) (except the fourth one) with one of the gluons replaced by a photon. The resulting cross section is obtained by making the replacement $\alpha_s^2 \to \alpha\alpha_s$, taking $\alpha=\beta=\gamma=\delta=1$ and multiplying Eq. (1) by the overall factor $Q^2/2$ (Q = charge of PGB).

Our results are collected in Table III. As shown in the first row the cross section for photoproduction of leptoquark pairs is below detectability limits due to the limited available phase space. In hadron-hadron collisions the $q\bar{q}$ annihilation mechanism is relevant only in $p\bar{p}$ scattering, as expected. In the one-family model there are four color octets ($P_8^0, P_8^3, P_8^+, P_8^-$) and four color triplets ($P_3^0, P_3^3, P_3^+, P_3^-$) with the corresponding antitriplets. If we are only interested in the production of pairs of PGB's, regardless of their quantum numbers other than color, the cross sections of Table III should be multiplied by a factor of 2 in the case of color octets and by a factor of 4 in the case of leptoquarks. At $\sqrt{s} = 500$ GeV, the available phase space is still very limited and the corre-

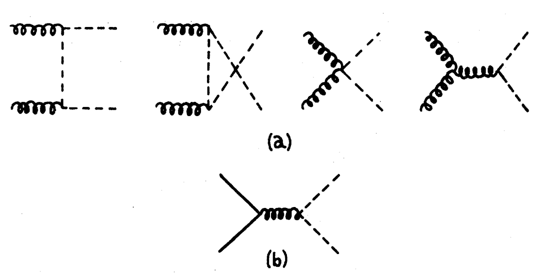

FIG. 1. Feynman diagrams for the subprocesses (a) $gg \to P\bar{P}$ and (b) $q\bar{q} \to P\bar{P}$. Curly lines are gluons, dashed lines are PGB's, and solid lines are quarks.

TABLE II. Numerical values for the parameters appearing in Eqs. (1) and (2).

	α	β	γ	δ	ρ
Color triplets (leptoquarks)	$\frac{5}{96}$	$\frac{31}{192}$	$\frac{1}{12}$	$-\frac{1}{96}$	$\frac{2}{9}$
Color octets	$\frac{15}{16}$	$\frac{51}{32}$	$\frac{9}{8}$	$\frac{9}{16}$	$\frac{4}{3}$

TABLE III. Cross sections for inclusive pair production of colored PGB's. In the fourth column $P_8\bar{P}_8$ stands for $P_8^+P_8^-$ or $P_8^0P_8^0+P_8^3P_8^3$. In the fifth column $P_3\bar{P}_3$ stands for $P_3^0\bar{P}_3^0$, $P_3^3\bar{P}_3^3$, $P_3^+\bar{P}_3^+$, or $P_3^-\bar{P}_3^-$. Q_P in the top right is the electric charge of the leptoquark ($\frac{2}{3}$, $\frac{2}{3}$, $\frac{5}{3}$, and $-\frac{1}{3}$ for P_3^0, P_3^3, P_3^+, and P_3^-, respectively).

Facility	Process	Subprocess	$\sigma_{P_8\bar{P}_8}$ (cm^2)	$\sigma_{P_3\bar{P}_3}$ (cm^2)
HERA $\sqrt{s}\sim 335$ GeV	$\gamma p\to P\bar{P}X$	$\gamma g\to P\bar{P}$	$\cdots$	$Q_P^2\times 7.8\times 10^{-41}$
CERN SPS collider $\sqrt{s}\sim 500$ GeV	$p\bar{p}\to P\bar{P}X$	$gg\to P\bar{P}$	3.5×10^{-56}	1.6×10^{-40}
		$q\bar{q}\to P\bar{P}$	1.7×10^{-50}	4.0×10^{-39}
ISABELLE $\sqrt{s}\sim 800$ GeV	$pp\to P\bar{P}X$	$gg\to P\bar{P}$	7.3×10^{-40}	6.7×10^{-38}
		$q\bar{q}\to P\bar{P}$	3.4×10^{-41}	7.9×10^{-39}
Fermilab collider $\sqrt{s}\sim 2000$ GeV	$p\bar{p}\to P\bar{P}X$	$gg\to P\bar{P}$	6.8×10^{-36}	6.7×10^{-36}
		$q\bar{q}\to P\bar{P}$	1.9×10^{-36}	3.0×10^{-36}

sponding cross sections are ridiculously small. At $\sqrt{s}=800$ GeV, i.e., ISABELLE, cross sections are still low, but with an assumed luminosity of 10^{32} cm^{-2} sec^{-1} one can still hope to see the leptoquark PGB's, since the calculated cross section implies a few hundred events a year. At $\sqrt{s}=2000$ GeV we may even detect the more massive color-octet PGB's. In fact, cross sections are roughly of the same order of magnitude as for the single production of colored hyper-η via the anomaly-dominated gluon-gluon fusion mechanism.

We expect the color-octet PGB's to decay mainly in heavy $q\bar{q}$ (Refs. 4, 6, and 7), i.e., $t\bar{t}$ in the case of $P_8^{0,3}$ and $t\bar{b}$ ($\bar{t}b$) in the case of P_8^+ (P_8^-). The decay channel into two gluons might also be very important for P_8^0 [for $m_t\gtrsim 20$ GeV, $\Gamma(P_8^0\to t\bar{t})/\Gamma(P_8^0\to gg)\gtrsim 4$]. For the other color-octet states, however, the corresponding decays into two gauge bosons are suppressed relative to the heavy $q\bar{q}$ channel. Consequently, there should be eight- or twelve-jet events for the pair-produced $P_8^{0,3}$, depending on the t-quark actual mass (a t quark will give two or three jets depending on whether $m_t>m_b+m_W$ or $m_t<m_b+m_W$, respectively). Analogously, we expect $P_8^\pm$ pair production to be signaled by the emission of six or eight jets, again depending on the actual mass of the top quark. Reconstruction of the mass of these PGB's ($\sim$250 GeV) will be of help in their definitive identification.

As far as background is concerned, the situation is far better than in single-PGB production (through anomalous ggP coupling), where the signal-to-noise ratio is $\sim$1.[6,7] Here the QCD subprocesses contributing to the background are $(q\bar{q},gg)\to t\,\bar{t}\,t\,\bar{t}$ for $P_8^{0,3}$ production and $(q\bar{q},gg)\to t\bar{b}\,\bar{t}b$ for $P_8^\pm$ production, and they are typically $O(\alpha_s^4)$ to be compared to the PGB production cross sections which are $O(\alpha_s^2)$.

The discussion concerning leptoquark signatures goes along the same lines. Here, however, the uncertainties associated with the implementation of extended hypercolor are even greater. A leptoquark, of course, decays into a lepton and a quark and, therefore, we expect two very energetic leptons along with two to four quark jets in the final state. In monophagic models, the couplings of leptoquarks to fermions have been computed.[4] Qualitatively, they couple also most strongly to the heaviest fermions available. Therefore, we expect dramatic decay signatures such as $t+\bar{\tau}$ or $t+\tau$.[12] The background here is even more suppressed than in the previous case, since to produce leptons, the mediation of photons is required. This makes the background of $O(\alpha^2\alpha_s^2)$ whereas the signal is of $O(\alpha_s^2)$.

Finally, we should comment on the discrimination between PGB pair production and ordinary-Higgs-boson pair production. As it is well known, colored Higgs bosons are expected in GUT's. In the minimal SU(5), there are color triplets and they must be superheavy, otherwise the proton would decay too fast. More bizzare Higgs realizations in GUT's might involve other SU(3) representations and, in general we cannot exclude the possibility that some of them are relatively light[13] ($<<10^{15}$ GeV). In ordinary colorless-scalar-boson pair production, the lowest-order diagrams all involve Higgs couplings to u and d quarks and therefore give negligible cross sections. On the other hand, if one avoids direct Yukawa couplings to quarks, one is forced to consider loops of heavy particles which make also smallish contributions to the production rates. Therefore, positive signals in hadron-hadron interactions exclude ordinary colorless-Higgs-scalar production and probably also colored-Higgs-scalar production if we stick to the standard SU(5) GUT with a 5- and 24-dimensional Higgs representation.

Our results can be summarized as follows. In principle, there are two advantages in pair production of colored PGB's. First, all colored PGB's can be produced through this mechanism whereas only neutral octets can be singly produced. Secondly, the signal-to-noise ratio is higher than in single production. On the other hand, phase-space limitations are stronger in pair production compared to single production. Moreover, discrimination between pair-produced PGB's and colored Higgs particles is only possible through a detailed analysis of their decays. The situation is better in single production, since Higgs particles cannot be produced via gluon-gluon or photon-gluon fusion at the tree level.

The Fermilab collider appears to be well suited for pair production of both color-octet and color-triplet PGB's. With an assumed luminosity of 10^{30} $cm^{-2} sec^{-1}$, a few hundred events per year should be produced. A similar situation occurs for single production of neutral isoscalar color octets (P_8^0).

At ISABELLE only pair-produced leptoquarks can be detected. With an assumed luminosity of 10^{32} cm^{-2} sec^{-1} we will again have a few hundred events per year. In this case the gluon-gluon mechanism dominates over the quark-antiquark annihilation mechanism. The production of color octets is below detectability limits except in the case of single production of P_8^0, where we expect a few thousand events per year.

At the CERN SPS collider (assuming $L = 10^{30}$ cm^{-2} sec^{-1}) both single and pair production are below detectability limits due to the insufficiency of available phase space. A similar situation occurs at HERA (where we have assumed an effective luminosity for photoproduction of 10^{31} cm^{-2} sec^{-1}) for pair production of leptoquarks. On the contrary, neutral octets can be detected since they are produced a the rate of a few hundred P_8^3 and a few tens of P_8^0 per year.

One thing we should stress, however. The results stated above were obtained neglecting scaling violations. At the energies considered, those corrections could be important. Unfortunately, we do not know the precise gluon distribution function at a given $Q_0{}^2$, from which we could derive its Q^2 evolution from QCD. Nevertheless, using the explicit Q^2 parton parametrization of Ref. 14 we have estimated their effect on our cross section. The relevant x values appearing in our problem are $x \simeq 0.7$, 0.4, and 0.2 for color-triplet production at $\sqrt{s} = 500$, 800, and 2000 GeV, respectively and $x \simeq 1$, 0.7, and 0.3 for color-octet production at $\sqrt{s} = 500$, 800, and 2000 GeV, respectively. Since at 500 GeV the calculated cross sections are already negligible, we do not consider them any further. At ISABELLE ($\sqrt{s} \simeq 800$ GeV) gluon-gluon annihilation is the most important mechanism and our estimates give an effect of two orders of magnitude suppression. A similar analysis for the quark distribution functions gives a smaller suppression, the overall effect being that PGB production at ISABELLE might probably be almost outside detectability limits. At the Tevatron collider, however, due to the smaller x values, the effects are not as dramatic and the suppression is about an order of magnitude for triplet production and somewhat larger for octet production.

A final remark is in order. If the hypercolor group is SU(N), the masses of the PGB's are proportional to $1/\sqrt{N}$.[2] Our numerical estimates correspond to $N = 4$. If N is greater than 4, the PGB masses would be accordingly reduced and phase-space limitations would become less severe. This could easily raise some of the cross sections of CERN SPS and HERA experiments to detectable values.

One of us (J.A.G.) acknowledges the hospitality of the Max-Planck-Institut (Munich) where part of this work was done and the Deutscher Akademischer Austauschdienst for financial support. This work was supported in part by the Instituto de Estudios Nucleares.

---

[1]L. Susskind, Phys. Rev. D 20, 2619 (1979); S. Weinberg, *ibid.* 19, 1277 (1979).

[2]For a review see, e.g., E. Farhi and L. Susskind, Phys. Rep. 74, 277 (1981) and references therein.

[3]E. Eichten, K. D. Lane, and J. Preskill, Phys. Rev. Lett. 45, 225 (1980).

[4]J. Ellis *et al.*, Nucl. Phys. B182, 529 (1981).

[5]A. Ali and M. A. B. Bég, Phys. Lett. 103B, 376 (1981); G. J. Gounaris and A. Nicolaidis, *ibid.* 102B, 144 (1981); J. A. Grifols, *ibid.* 102B, 277 (1981).

[6]S. Dimopoulos, S. Raby, and G. L. Kane, Nucl. Phys. B182, 77 (1981).

[7]G. Girardi, P. Mery, and P. Sorba, Nucl. Phys. B195, 410 (1982).

[8]J. A. Grifols and A. Méndez, Phys. Rev. D 25, 253 (1982).

[9]See, e.g., Refs. 2 and 6 and references therein.

[10]The coupling of a *physical* Higgs particle to two gauge bosons vanishes at the tree level when one or both gauge bosons are massless. This is a direct consequence of gauge invariance under the group generated by the unbroken generator associated with the massless gauge boson. Thus, the Hgg and $Hg\gamma$ couplings are zero at the tree level.

[11]P. Langacker, Phys. Rep. 72, 185 (1981).

[12]G. Barbiellini *et al.*, DESY Report No. 81-064, 1981 (unpublished).

[13]L. Ibañez, Nucl. Phys. B181, 105 (1981).

[14]K. Kato, Y. Shimitsu, and H. Yamamoto, Prog. Theor. Phys. 63, 1295 (1980).