Possible mechanism for inclusive production of η mesons in hadron-hadron collisions

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A mechanism is proposed for the inclusive production of η mesons in hadron-hadron collisions on the basis of the idea of the production of a $G(1590)$ meson[4] in the coalescence of the gluons of colliding hadrons. This meson decays primarily by channels containing η mesons. The cross section for the inclusive production of η mesons in pp and $p\tilde{p}$ collisions is estimated and found to be given approximately by the expression

$$\sigma_\eta^{\rm incl} = 4.5[\ln(s/M_G^2) - 4.6] \times 10^{-28}\ {\rm cm}^2.$$

At collider energies ($\sqrt{s} = 540$ GeV) the cross section would be $\sigma_\eta^{\rm incl} \cong 3.2$ mb, so that the yield of η mesons in $p\tilde{p}$ collisions would be close to that observed experimentally.

Analysis of the multiple production of particles in high-energy hadron-hadron collisions (at the energies of the ISR and the collider, $\sqrt{s} = 60$ and 540 GeV, respectively) indicates that the number of η mesons which are produced at large angles in these interactions is a significant fraction of the number of π^0 mesons that are produced. According to data from the UA-2 experiment, for example, the ratio of the average number of η mesons produced to the average number of π^0 mesons is 0.55 for the angular interval $40° \leqslant \theta \leqslant 140°$ and for the $p_\perp$ interval from 1.5 to 4.5 GeV/c. According to data from the UA-5 experiment,[2] the ratio $\langle\eta\rangle/\langle\pi^0\rangle$ for $|\eta| < 5$ (η is the pseudorapidity) is 0.3 ± 0.1. Similar values are found from cosmic-ray studies at energies above[3] 100 TeV.

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It is thus interesting to consider possible mechanisms for the inclusive production of η mesons in hadron-hadron collisions which could explain the yield of η mesons with respect to the yield of π^0 mesons in high-energy central collisions. Of interest in this connection are the unusual decay properties of the meson $G(1590)$, recently observed by a collaboration from the Institute of High-Energy Physics and CERN.[4] The $G(1590)$ meson, with a mass of 1592 ± 25 MeV, a total width $\Gamma^G_{\rm tot} = 240 \pm 40$ MeV, and quantum numbers $J^{PC} = 0^{++}$, decays primarily in channels containing η mesons: $G \to \eta\eta$, $G \to \eta\eta'$, with $Br(G\to\eta\eta')/Br(G\to\eta\eta) = 2.7 \pm 0.8$ (Ref. 5). An important point is that here we have $Br(G\to\pi^0\pi^0)/Br(G\to\eta\eta) < 0.3$ and $Br(G\to K\bar{K})/Br(G\to\eta\eta) < 0.6$. These decay properties of the G meson have been interpreted by Gershtein *et al.*[6] as a reflection of its two-gluon nature; i.e., the G meson is a glueball.

Let us assume that the G meson is a glueball or, at any rate, that the partial width for the decay $G \to gg$ is large, comparable to the total width $\Gamma^G_{\rm tot}$. In this case the G meson can be formed effectively in high-energy hadron-hadron collisions by a mechanism of a coalescence of gluons. This mechanism was first discussed by Ellis and Einhorn[7] in connection with the problem of the production of η_c production in hadron-hadron collisions. It was subsequently used by the same investigators and Quigg[8] to study the production of the J/ψ particles through χ_c states. The corresponding expression[7] for the total cross section for the production of a G meson by this mechanism, in the collision of hadrons A and B, is

$$\sigma(A + B \to G + X) = \frac{1}{64}\,\frac{8\pi^2}{M_G^3}\,\Gamma^G_{tot}\,\tau \int_\tau^1 F_g^A(x) F_g^B\Big(\frac{\tau}{x}\Big)\frac{dx}{x} \,. \qquad (1)$$

Here $\tau = M_G^2/s$, F_g^A and F_g^B are the gluon distribution functions in hadrons A and B, and the factor of $1/64$, associated with color, has been singled out explicitly. As we have already mentioned, we are assuming that $\Gamma(G\to gg) \cong \Gamma^G_{\rm tot}$.

The cross section $\sigma(A + B \to G)$ has been calculated primarily for pp and $p\tilde{p}$ collisions. In this case, "naive" distribution functions[9]

$$F_g^p(x) = F_g^{\tilde{p}}(x) = 3\,(1-x)^5/x \qquad (2)$$

have been used as $F_g^{A,B}(x)$. The naive distribution functions, however, have been confirmed experimentally reasonably well, e.g., a recent analysis of J/ψ production through χ_c production in nucleon-nucleon collisions.[10] Substitution of (2) into (1) leads to the expression

$$\sigma(NN \to G) = \frac{9\pi^2}{8M_G^3}\,\Gamma^G_{tot}\,\Big(\ln\frac{s}{M_G^2} - 4.6\Big). \qquad (3)$$

If we assume $\Gamma^G_{\rm tot} = \Gamma^G_{\eta\eta} + \Gamma^G_{\eta\eta'}$, and use $\Gamma^G_{\eta\eta'}/\Gamma^G_{\eta\eta} \cong 3$, i.e., $Br(G\to\eta\eta) = 1/4$, and $Br(G\to\eta\eta') = 3/4$, we find that the yield of η mesons is determined by the cross section

$$\sigma_\eta^{incl}(NN) = \sigma(NN\to G)\,[Br(G\to\eta\eta)\times 2 + Br(G\to\eta\eta')\times 1.65] = 1.74\,\sigma(NN\to G). \qquad (4)$$

The factors of 2 and 1.65 in the brackets reflect the production of two η mesons in the decay of a G meson by the $G \to \eta\eta$ mechanism and an average of 1.65 η mesons in the decay $G \to \eta\eta'$.

The numerical value of $\sigma_{\eta}^{\mathrm{incl}}(NN)$ for the collider energy ($\sqrt{s} = 540$ GeV) is about 3.2 mb. This value should be compared with the value of $\sigma_{\pi^0}^{\mathrm{incl}}(NN)$, corresponding to central (not diffractive) collisions, i.e., collisions with a finite $p_\perp$. In the actual UA-2 experiment, the yields of the η mesons and the π^0 mesons are comparable in the $p_\perp$ interval 1.5–4.5 GeV/c and at $40° \leqslant \theta \leqslant 140°$. Since the inclusive production of π^0 mesons in this experiment is described well by the function

$$E\frac{d^3\sigma}{dp^3} = A\left(\frac{2}{1+p_\perp}\right)^n, \tag{5}$$

where $A = 1.43$ mb/(GeV^2/c^3),and $n = 8$, it is a straightforward matter to estimate the total cross section for the production of π^0 mesons under these conditions. We find $\bar{\sigma}_{\pi^0}^{\mathrm{incl}}(NN) = 1.8$ mb. To estimate the corresponding cross section for η mesons, we must specify a definite $p_\perp$ dependence of the differential cross section for the production of the G meson, whose decay gives rise to the production of the η mesons. In the model which has been discussed earlier, we would have $p_\perp \equiv 0$. The additional smearing along the $p_\perp$ scale that arises in the decays $G \to \eta\eta$ and $G \to \eta\eta'$ can be ignored in a first approximation, since the scale values of the momenta acquired by the η mesons in the decay are small in comparison with the $p_\perp$ interval in which the observations are carried out. As a rough estimate we can use the $p_\perp$ distribution of the gluon jets that arise in hadron-hadron collisions (by virtue of the interaction of two gluons) according to QCD calculations.[11] We assume that the gluon jet is replaced by a G meson for our purposes. Following Ref. 11, we find

$$\frac{d^3\sigma}{dy\,dp_\perp^2} = (p_\perp^2)^{F(k_1)+F(k_2)-2}, \tag{6}$$

where $k_{1,2} = 12.7\left[\ln(\sqrt{s}/p_\perp) \pm y\right]/\ln^2(p_\perp^2/\Lambda^2)$, and

$$F(k) = \begin{cases} [k(1-0.21\ln k)]^{1/2}, & k \leqslant 1 \\ 1 & k > 1. \end{cases}$$

$$\Lambda = 63 \text{ MeV}$$

Analysis of (6) shows that the y dependence of $d^3\sigma/dy\,dp_\perp^2$ is weak, at least in the interval of interest here, $-1 \lesssim y \lesssim 1$, and we can set $y = 0$ for the purposes of the discussion below. We introduce $(d^3\sigma/dy\,dp_\perp^2)_{y=0} = f(p_\perp^2)$, and in the integration over x (i.e., over the longitudinal momentum of the G meson) in (1) we note that at the given values $\theta_{\min} = 40°$ and $\theta_{\max} = 140°$ a definite value of $(p_\perp)_{\min}$ is associated with each value of x. The modification of expression (1) is

$$\sigma(NN \to G) = \frac{1}{64}\,\frac{8\pi^2}{M_G^3}\,\Gamma_{tot}^G\,\tau\int_\tau^1 F_g^N(x)F_g^N\left(\frac{\tau}{x}\right)\frac{\int_{(p_\perp)_{min}}^{(p_\perp)_{max}} p_\perp f(p_\perp^2)\,dp_\perp}{\int_0^\infty p_\perp f(p_\perp^2)\,dp_\perp}\,\frac{dx}{x}, \tag{7}$$

where $(p_\perp)_{max} = 4.5$ GeV, $(p_\perp)_{min} = \max\{1.5 \text{ GeV}, |p_\parallel| \tan 40°\}$, and $(p_\parallel) = (x - \tau/x)\sqrt{s}/2$. An estimate from this expression yields $\bar{\sigma}_G^{incl}(NN) = 0.26$ mb or $\bar{\sigma}_\eta^{incl}(NN) = 0.45$ mb. Since $\bar{\sigma}_{\pi^0}^{incl}(NN)$ is 1.8 mb for these conditions, we have $\langle\eta\rangle/\langle\pi^0\rangle = 0.25$, in fair agreement with experimental data. This result appears to mean that the production of η mesons through the production and decay of a G meson may in fact be an important mechanism for the inclusive production of η mesons at high energies.

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