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Hadron production from quark fireballs and CERN SPS Collider results

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The hadron-production model developed in Phys. Rev. D 23, 2554 (1981) gives a charged-hadron multiplicity in reasonable agreement with the CERN SPS Collider results at $E_{\text{c.m.}} = 540$ GeV, if the production of particles heavier than pions during fireball decay is considered.

Quark fireball models for hadron production were developed in Refs. 1–4. In these models, secondary hadrons are produced by isotropic decay of the fireballs in the fireball c.m. All secondary hadrons were assumed to be pions. The average number of final-state hadrons produced by a fireball is found by dividing the fireball invariant mass by the effective mass m_H of the secondary hadrons. In Refs. 1–4, m_H was taken as

$$m_H = (m_\pi{}^2 + p_H{}^2)^{1/2} \quad ,$$

where m_π is the pion rest mass and $|\vec{p}_H| = 440$ MeV/c is the average momentum of secondary hadrons in the fireball rest frame. At the quark level, the models of Refs. 1–4 consider production of u and d quark-antiquark pairs only. Fireballs develop from excited quark-antiquark ($Q\bar{Q}$) pairs. They decay by subsequent production of u and d $Q\bar{Q}$ pairs, and recombination of the quarks and antiquarks into pions.

At very high energies, the average charged-hadron multiplicities observed should be lower than predicted by the models in Refs. 1–4. This is because some of the fireball energy will go into producing hadrons more massive than pions when the fireball invariant mass m^* exceeds the threshold for kaon production. However, at energies currently accessible in e^+e^- and lepton-nucleon reactions, and at c.m. energies below about 60 GeV in nucleon-nucleon scattering, fireball invariant masses are low enough that production of hadrons heavier than pions can be neglected. So at these energies, the models described in Refs. 1–4 give results in reasonable agreement with experiment.

A high-energy approximation developed in Ref. 3 (calculation A and Table V of Ref. 3) predicted an average charged multiplicity of $\langle n_{\text{ch}} \rangle = 33.74$ at $E_{\text{c.m.}} = 500$ GeV in $p\bar{p}$ collisions. This prediction assumed all secondary hadrons were pions and the contribution from annihilation reactions at high energy is negligible, so the charged multiplicity is approximately the same in pp and $p\bar{p}$ reactions. Experimental results[5] from the CERN Super Proton Synchrotron (SPS) Collider give $\langle n_{\text{ch}} \rangle = 27.4 \pm 2.0$ at $E_{\text{c.m.}} = 540$ GeV, indicating a charged multiplicity considerably lower than that predicted in Ref. 3.

This Brief Report demonstrates that an approximate treatment of the production of strange-quark–antiquark pairs and of diquark-antidiquark in the model of Ref. 3 results in a charged multiplicity which agrees with the SPS Collider data. Furthermore, the satisfactory results obtained for $\langle n_{\text{ch}} \rangle$ in e^+e^- and lepton-nucleon scattering in the energy ranges considered in Refs. 1, 2, and 4 are not destroyed.

Reference 3 assumed that the probability of a constituent quark carrying a fraction x of the incident proton momentum is

$$f^c(x) = 20x(1-x)^3 \quad .$$

Hwa[6] suggests that the distribution

$$f^H(x) = \tfrac{105}{16} x^{1/2}(1-x)^2$$

is more appropriate. Using Hwa's constituent-quark momentum distribution in the high-energy approximation of Ref. 3 (calculation A) to estimate $\langle n_{\text{ch}} \rangle$ in $p\bar{p}$ scattering at $E_{\text{c.m.}} = 500$ GeV results in $\langle n_{\text{ch}} \rangle = 33.24$. This compares with $\langle n_{\text{ch}} \rangle = 33.74$ when the original distribution $f^c(x)$ is used. Thus, the model developed in Ref. 3 is not particularly sensitive to changes in the constituent quark momentum distribution. Nevertheless, Hwa's distribution function $f^H(x)$ is used in the nucleon-nucleon scattering calculations discussed in the remainder of this Brief Report. Using Hwa's distribution function in calculation A of Ref. 3, the estimated value of $\langle n_{\text{ch}} \rangle$ in $p\bar{p}$ scattering at $E_{\text{c.m.}} = 540$ GeV is $\langle n_{\text{ch}} \rangle = 34.5$, 26% higher than the experimental value $\langle n_{\text{ch}} \rangle = 27.4 \pm 2.0$.

To estimate the effects of producing hadrons heavier than pions, assume the following:

(a) Only u, d, and s quarks and antiquarks are produced.

(b) When the fireball invariant mass is large, u, d, and s quarks are produced in the ratio[7] 2:2:1, and diquark-antidiquark pairs are produced instead of $Q\bar{Q}$ pairs 10% of the time.

(c) Only the lowest-lying $S=0$ and $S=1$ mesons and baryons are considered.

Then at asymptotic energies, 10% of the quark fireball decay products will be baryons, 84% will be pions, and 16% will be kaons. 38.4% of the baryons (or 3.84% of the fireball decay products) will be Λ's, and the rest of the baryons will be taken as nucleons.

Two more assumptions are made to parametrize the threshold behavior for producing particles of different types:

(d) Kaon production grows like two-body phase space from the effective threshold at

$$m^*=2(m_K^2+p_H^2)^{1/2} \ ,$$

where m_K is the kaon mass, to a constant fraction $F_{mK}=0.16$ of all mesons when

$$0.16m^*=2(m_K^2+p_H^2)^{1/2} \ .$$

(e) Baryon production grows like two-body phase space from the effective threshold at

$$m^*=2(m_N^2+p_H^2)^{1/2} \ ,$$

where m_N is the nucleon mass, to a constant fraction $F_B=0.1$ of all secondary hadrons when

$$0.1m^*=2(m_N^2+p_H^2)^{1/2} \ .$$

Since the nucleon and Λ effective masses are nearly degenerate, the fraction $F_B=0.384$ of baryons produced from fireballs with invariant mass greater than the effective Λ threshold at

$$m^*=2(m_\Lambda^2+p_H^2)^{1/2} \ ,$$

where m_Λ is the Λ mass, will be taken as Λ's and the remainder of the baryons will be considered nucleons.

Under the above assumptions, the average effective mass $\overline{m}_H$ of a secondary hadron as a function of the fireball invariant mass m^* is

$$\begin{aligned}\overline{m}_H(m^*)&=[1-F_B g_D(m^*)]\{[1-F_{mK}g_S(m^*)](m_\pi^2+p_H^2)^{1/2}+F_{mK}g_S(m^*)(m_K^2+p_H^2)^{1/2}\}\\&\quad+F_B g_D(m^*)\{[1-F_{B\Lambda}\theta(m^*-2(m_\Lambda^2+p_H^2)^{1/2})](m_N^2+p_H^2)^{1/2}+F_{B\Lambda}\theta(m^*-2(m_\Lambda^2+p_H^2)^{1/2})(m_\Lambda^2+p_H^2)^{1/2}\}\ ,\end{aligned}$$

and the average charge of a secondary-hadron pair is

$$\overline{p}_c=[1-F_B g_D(m^*)]\{\tfrac{2}{3}[1-F_{mK}g_S(m^*)]+0.5F_{mK}g_S(m^*)\}+F_B g_D(m^*)\{0.5[1-F_{B\Lambda}\theta(m^*-2(m_\Lambda^2+p_H^2)^{1/2})]\} \ .$$

Here, $g_S(m^*)$ and $g_D(m^*)$ are the threshold functions for strange-quark—antiquark pair production and for diquark-antidiquark production, respectively:

$$g_S(m^*)=\begin{cases}0 \ \text{for } m^*\leq 2(m_K^2+p_H^2)^{1/2}\\ \dfrac{m^*[0.25m^{*2}-(m_K^2+p_H^2)]^{1/2}}{2(m_K^2+p_H^2)(F_{mK}^{2}-1)^{1/2}} \ \text{for } 2(m_K^2+p_H^2)^{1/2}<m^*<\dfrac{2(m_K^2+p_H^2)^{1/2}}{F_{mK}}\ ,\\ 1 \ \text{for } m^*\geq\dfrac{2(m_K^2+p_H^2)^{1/2}}{F_{mK}}\ ,\end{cases}$$

$$g_D(m^*)=\begin{cases}0 \ \text{for } m^*< 2(m_N^2+p_H^2)^{1/2}\\ \dfrac{m^*[0.25m^{*2}-(m_N^2+p_H^2)]^{1/2}}{2(m_N^2+p_H^2)(F_B^{2}-1)^{1/2}} \ \text{for } 2(m_N^2+p_H^2)^{1/2}<m^*<\dfrac{2(m_N^2+p_H^2)^{1/2}}{F_B}\ ,\\ 1 \ \text{for } m^*\geq\dfrac{2(m_N^2+p_H^2)^{1/2}}{F_B}\ ,\end{cases}$$

$\theta(x)$ is the Heaviside step function, $\theta(x)=0$ for $x\leq 0$, $\theta(x)=1$ for $x>0$.

Using these approximations for the average effective mass of a secondary hadron and the average charge of a secondary-hadron pair in calculation A of Ref. 3 gives an estimate of the charged multiplicity in high-energy nucleon-nucleon scattering when secondary hadrons heavier than pions are considered. At 62.8 GeV in the c.m., the result is $\langle n_{ch}\rangle=11.99$, compared with the experimental value[8] $\langle n_{ch}\rangle=12.70$ and the all-pion results in Table II of Ref. 3 which range from 12.89 to 13.63. At 150 GeV in the c.m., the new result is $\langle n_{ch}\rangle=16.75$, compared to the all-pion results in Table II of Ref. 3, which range from 18.87 to 20.14. At 540 GeV in the c.m., the new result is $\langle n_{ch}\rangle=27.83$, in reasonable agreement with the experimental result[5] of $\langle n_{ch}\rangle=27.4\pm 2.0$, assuming that multiplicities in pp and $p\overline{p}$ scattering are approximately equal at high energies.

It is now necessary to see if a similar treatment of the average mass and average charge of secondary hadrons in the electron-positron annihilation and lepton-hadron calculations reported in Refs. 1, 2, and 4 destroys the satisfactory results obtained previously. Obviously, any changes would be most apparent at high c.m. energies, so attention can be concentrated there. In electron-positron annihilation, the all-pion result of $\langle n_{\rm ch}\rangle = 11.525$ at 31.8 GeV in the c.m. changes to $\langle n_{\rm ch}\rangle = 11.351$ when production of heavier secondaries is considered using the approximation discussed in this report. Correspondingly, the all-pion result of $\langle n_{\rm ch}\rangle = 7.73$ at $W^2 = 200\ \text{GeV}^2$ in $\nu + p \rightarrow \mu^- +$hadrons changes to $\langle n_{\rm ch}\rangle = 7.68$ when the production of secondaries heavier than pions is considered using the method outlined in this Brief Report.

These approximate calculations indicate that fireball decay models provide reasonable estimates of secondary-hadron multiplicities even at very high energies.

Finally, Chiu and Xie[9] suggest that the same mechanism may produce secondary hadrons in diffraction dissociation and central production processes, eliminating the need for two-component models. Following this lead, one can identify the production of secondary hadrons by target or beam quarks which emit gluons after a hadronic collision as diffraction-dissociation events. According to Ref. 3, the sum of beam and target single-diffraction-dissociation events at high energies should then be constant at

$$P_{QB}{}^2(0)P_{QT}(0)[1-P_{QT}(0)] + P_{QT}{}^2(0)P_{QB}(0)[1-P_{QB}(0)] = 18.4\% \ ,$$

which also agrees with the experimental results[5] reported at the CERN SPS Collider.

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