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Hyperfine Splitting in Light-Flavour Hadron Production at LEP

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Layout

- Known features of baryon and strangeness suppression
- Constituent quark model
- LEP 1 results on
 - total hadron production rates
 - direct hadron production rates using:
 - *JETSET model*
 - *Yi-Jin Pei model*
- Comparison of LEP 1 results with hadronic reactions and heavy nuclear collisions
- Summary

Strangeness suppression

$$\lambda = \frac{2\langle s\bar{s} \rangle}{\langle u\bar{u} \rangle + \langle d\bar{d} \rangle}$$

Hadron colliders

UA1 (*combining with other results*):

$$\lambda = 0.290 \pm 0.015$$

LEP experiments

From JETSET tuning to the data:

$$\lambda = 0.285 \pm 0.015 \quad ALEPH$$

$$\lambda = 0.307 \pm 0.007 \pm_{0.017}^{0.002} \quad DELPHI$$

From the ratios of particle rates (ALEPH):

$$\langle K^{*0} \rangle / \langle \rho^0 \rangle = 0.29 \pm 0.01 \pm 0.05$$

$$\langle \phi \rangle / \langle K^{*0} \rangle = 0.29 \pm 0.01 \pm 0.04$$

$$\langle \Xi^- \rangle / \langle \Sigma^0 \rangle = 0.36 \pm 0.10$$

Baryon suppression

Anisovich, Shekhter (1973): $B/M = \bar{B}/M = 1/6$

JETSET:

- $qq/q = 0.10$, $(us/ud)/\lambda = 0.40$
- $\frac{1}{3}(qq_1/qq_0) = 0.05$, popcorn parameter

HERWIG and UCLA:

baryons are suppressed because they are heavier

Chliapnikov, Uvarov (1995):

$$\frac{(2I_m + 1)\langle n \rangle}{2J + 1} = A e^{-BM^2}$$

Becattini (1996): Thermodynamical model

Yi-Jin Pei (1996):

$$\langle n \rangle = C \cdot \frac{2J + 1}{C_B} \cdot \lambda^k \cdot e^{-E_{bind}/T}$$

Quark Model

Perfect SU(3): masses and rates are the same

Differences between SU(3) multiplets:

mass dependence of hyperfine splitting

electromagnetic effects, binding energies etc

Gasiorowicz, Rosner (1981):

$$M_{mes} = m_1 + m_2 + A \frac{(\mathbf{S}_1 \cdot \mathbf{S}_2)}{m_1 m_2}$$
$$M_{bar} = m_1 + m_2 + m_3 + A' \left(\frac{\mathbf{S}_1 \cdot \mathbf{S}_2}{m_1 m_2} + \frac{\mathbf{S}_1 \cdot \mathbf{S}_3}{m_1 m_3} + \frac{\mathbf{S}_2 \cdot \mathbf{S}_3}{m_2 m_3} \right)$$

$$\hat{m} = m_u = m_d$$

Mesons:

$$\begin{array}{ll} \hat{m} = 310 \text{ MeV}/c^2 & m_s = 483 \text{ MeV}/c^2 \\ A = (2\hat{m}/\hbar)^2 160 \text{ MeV}/c^2 & m_s - \hat{m} = 173 \text{ MeV}/c^2 \end{array}$$

Baryons:

$$\begin{array}{ll} \hat{m} = 363 \text{ MeV}/c^2 & m_s = 538 \text{ MeV}/c^2 \\ A' = (2\hat{m}/\hbar)^2 50 \text{ MeV}/c^2 & m_s - \hat{m} = 175 \text{ MeV}/c^2 \end{array}$$

LEP Data

The rates measured by different LEP experiments were averaged

In calculating the errors, the PDG procedure was applied

For the Λ total rate, the contributions from $\Sigma^0 \rightarrow \Lambda\gamma$ and weak decay of Ξ and Ω^- were subtracted

Antiparticles were not included into the definition of the rates

In the subsequent fits, the rates of hadrons belonging to the same isospin multiplets were averaged

Meson Rates at LEP 1

Particle	Total rate	Experiment
π^0	9.43 ± 0.38	ADLO
π^+	8.53 ± 0.24	ADO
K^0	1.007 ± 0.012	ADLO
K^+	1.13 ± 0.03	ADO
η	0.90 ± 0.07	ALO
η'	0.16 ± 0.03	ALO
$f_0(980)$	0.147 ± 0.011	DO
$a_0^+(980)$	0.14 ± 0.06	O
ρ^0	1.24 ± 0.10	AD
ρ^+	1.20 ± 0.22	O
ω	1.09 ± 0.09	ALO
ϕ	0.097 ± 0.007	ADO
$K^{*0}(892)$	0.379 ± 0.017	ADO
$K^{*+}(892)$	0.359 ± 0.022	ADO
$f_2(1270)$	0.169 ± 0.025	DO
$K_2^{*0}(1430)$	0.043 ± 0.022	DO
	0.037 ± 0.013	D
	0.119 ± 0.044	O
$f_2'(1525)$	0.012 ± 0.006	D

Baryon Rates at LEP 1

Particle	Total rate	Experiment
p	0.52 ± 0.02	ADO
Λ	0.122 ± 0.006	ADLO
Σ^+	0.044 ± 0.004	DO
Σ^0	0.037 ± 0.005	ADO
Ξ^-	0.0133 ± 0.0006	ADO
$\Delta^{++}(1232)$	0.044 ± 0.018	DO
	0.040 ± 0.008	D
	0.110 ± 0.029	O
$\Sigma^{*+}(1385)$	0.0118 ± 0.0011	ADO
$\Xi^{*0}(1530)$	0.0029 ± 0.0005	ADO
Ω^-	0.0006 ± 0.0001	ADO
$\Lambda(1520)$	0.0107 ± 0.0014	O

Total Production Rates

Exponentials with the same slope for baryons,
vector and tensor mesons:

$$b = 9.91 \pm 0.11 \text{ (GeV/c}^2\text{)}^{-1}, \chi^2/ndf = 33/11$$

$$b = 9.88 \pm 0.11 \text{ (GeV/c}^2\text{)}^{-1}, \chi^2/ndf = 11/10$$

Strangeness suppression factors

ϕ/ρ^0	0.279 ± 0.015
ϕ/K^{*0}	0.255 ± 0.022
K^{*0}/ρ^0	0.305 ± 0.028
f_2'/f_2	0.27 ± 0.07
f_2'/K_2^{*0}	0.28 ± 0.20
K_2^{*0}/f_2	0.25 ± 0.13
Ξ^-/p	0.160 ± 0.005
Ξ^-/Λ	0.109 ± 0.007
Ξ^-/Σ^+	0.305 ± 0.032
Λ/p	0.235 ± 0.015
Σ^+/p	0.084 ± 0.008
Ω^-/Δ^{++}	0.24 ± 0.04
Ω^-/Σ^{*+}	0.23 ± 0.02
Ω^-/Ξ^{*0}	0.21 ± 0.05
Ξ^{*0}/Σ^{*+}	0.25 ± 0.05
Ξ^{*0}/Δ^{++}	0.26 ± 0.06
Σ^{*+}/Δ^{++}	0.27 ± 0.11
$\Xi^{*0}/\Lambda(1520)$	0.37 ± 0.08

Longstanding problem for octet baryons:
small λ from Ξ^-/p , Ξ^-/Λ and Σ^+/p ratios

Total Production Rates versus Sum of Quark Masses

Difference between the pseudoscalar and vector meson rates and the octet and decuplet baryon rates can be explained, at least partly, by the hyperfine mass splitting

Vector-to-Pseudoscalar and Decuplet-to-Octet Suppressions for Total Rates

$$M_\rho - M_\pi = 640 \text{ MeV}/c^2$$

$$M_{K^*} - M_K = 411 \text{ MeV}/c^2$$

$$M_{\Delta^{++}} - M_p = 300 \text{ MeV}/c^2$$

$$M_{\Sigma^*} - M_{\Sigma^+} = M_{\Xi^{*0}} - M_{\Xi^-} = 202 \text{ MeV}/c^2$$

$$\frac{\rho}{3\pi} < \frac{K^*(896)}{3K} < \frac{\Delta^{++}(1232)}{2p} < \frac{\Sigma^{*+}(1385)}{2\Sigma^+} = \frac{\Xi^{*0}(1530)}{2\Xi^-}$$

$$\rho/(3\pi) = 0.048 \pm 0.004$$

$$\Delta^{++}/(2p) = 0.042 \pm 0.017$$

$$K^*(896)/(3K) = 0.120 \pm 0.005$$

$$\Sigma^{*+}(1385)/(2\Sigma^+) = 0.135 \pm 0.018$$

$$\Xi^{*0}(1530)/(2\Xi^-) = 0.11 \pm 0.02$$

$$\begin{aligned} \frac{\rho}{3\pi} &= \frac{\Delta^{++}(1232)}{2p} \\ \frac{K^*(896)}{3K} &= \frac{\Sigma^{*+}(1385)}{2\Sigma^+} = \frac{\Xi^{*0}(1530)}{2\Xi^-} \end{aligned}$$

Direct Production Rates

$$\langle n \rangle_{Direct} = \langle n \rangle_{Total}^{LEP} \cdot Fraction$$

Fraction: JETSET and Yi-Jin Pei models

$\langle n \rangle_{Direct}$ $\neq$ model-predicted rates!

All light flavour hadrons up to a mass of 2.5 GeV/c² in the meson and baryon PDG were included in the Pei Model

Additional 10% systematic errors for octet baryons and 5% errors for all other hadrons

Direct Rates

Particle	JETSET Model	Pei Model
π^+	1.37 ± 0.07	1.54 ± 0.08
K^+	0.305 ± 0.017	0.260 ± 0.014
η	0.298 ± 0.027	0.271 ± 0.024
η'	0.126 ± 0.027	0.094 ± 0.020
ρ^0	0.67 ± 0.06	0.58 ± 0.05
ω	0.62 ± 0.06	0.52 ± 0.05
$K^{*0}(892)$	0.228 ± 0.015	0.186 ± 0.013
ϕ	0.068 ± 0.006	0.062 ± 0.005
$f_2(1270)$	0.162 ± 0.025	0.132 ± 0.021
$K_2^{*0}(1430)$	0.041 ± 0.020	0.042 ± 0.020
$f_2'(1525)$	0.012 ± 0.006	0.012 ± 0.006
p	0.29 ± 0.03	0.062 ± 0.007
Λ	0.082 ± 0.008	0.022 ± 0.002
Σ^+	0.038 ± 0.005	0.018 ± 0.003
Σ^0	0.032 ± 0.005	0.015 ± 0.002
Ξ^-	0.0100 ± 0.0011	0.0055 ± 0.0006
$\Delta^{++}(1232)$	0.042 ± 0.017	0.030 ± 0.012
$\Sigma^{*+}(1385)$	0.0108 ± 0.0012	0.0107 ± 0.0012
$\Xi^{*0}(1530)$	0.0027 ± 0.0005	0.0027 ± 0.0005
Ω^-	0.00055 ± 0.00010	0.00053 ± 0.00010

Vector-to-Pseudoscalar and Decuplet-to-Octet Suppressions for Direct Rates

Ratios	JETSET model	Pei model
$\rho/(3\pi)$	0.164 ± 0.015	0.126 ± 0.012
$K^*(896)/(3K)$	0.244 ± 0.016	0.239 ± 0.015
$\Delta^{++}(1232)/(2p)$	0.07 ± 0.03	0.24 ± 0.10
$\Sigma^{*+}(1385)/(2\Sigma^+)$	0.14 ± 0.03	0.29 ± 0.05
$\Xi^{*0}(1530)/(2\Xi^-)$	0.14 ± 0.03	0.25 ± 0.05

V/PS for both models are compatible
D/O are a factor of 2-3 smaller for JETSET

Relations

$$\frac{\rho}{3\pi} = \frac{\Delta^{++}(1232)}{2p}$$

$$\frac{K^*(896)}{3K} = \frac{\Sigma^{*+}(1385)}{2\Sigma^+} = \frac{\Xi^{*0}(1530)}{2\Xi^-}$$

seen for the total rates are also satisfied for the
direct rates reconstructed with the Pei model,
but not with JETSET

Direct Rates with JETSET Model

$$\lambda = e^{-(m_s - \hat{m})/T}$$

$$\lambda_M = 0.289 \pm 0.006, \quad \lambda_B = 0.285 \pm 0.006$$

Direct Rates with Pei Model

Fits to two exponentials ($\chi^2/ndf = 13/8$):

$$\lambda_M = 0.297 \pm 0.004, \quad \lambda_B = 0.293 \pm 0.004$$

Good agreement with usually accepted λ , but no evidence for additional suppression of strange baryons. No problems with the octet-baryons

Strangeness Suppression for Tensor Mesons

$$\langle f_2(1270) \rangle_{dir} = 0.132 \pm 0.021, \quad \lambda = 0.295 \pm 0.006$$

$\Downarrow$

$$\langle K_2^{*0}(1430) \rangle = 0.039 \pm 0.006$$

$$\langle f_2'(1525) \rangle = 0.011 \pm 0.02$$

To be compared with:

$$\begin{array}{llll} \langle K_2^{*0} \rangle & = & 0.043 \pm 0.022 & \text{(DELPHI: } 0.037 \pm 0.013) \\ & & & \text{(OPAL: } 0.119 \pm 0.044) \\ \langle f_2' \rangle & = & 0.012 \pm 0.006 & \text{(DELPHI)} \end{array}$$

Hyperfine Splitting between Baryon Rates

$$\begin{aligned} M_{\Sigma^0} - M_{\Lambda} &= 65 \text{ MeV}/c^2 \\ \langle \Sigma^0 \rangle &= \langle \Lambda \rangle e^{-(M_{\Sigma^0} - M_{\Lambda})/T} \\ \left(\frac{\Sigma^0}{\Lambda}\right)_{HS} &= 0.634 \pm 0.004 \end{aligned}$$

$$\begin{aligned} \left(\frac{\Sigma^0}{\Lambda}\right)_{LEP}^{Pei} &= 0.66 \pm 0.08 \\ \left(\frac{\Sigma^0}{\Lambda}\right)_{LEP}^{JETSET} &= 0.39 \pm 0.05 \end{aligned}$$

$$\begin{aligned} M_{\Delta^{++}} - M_p &= 300 \text{ MeV}/c^2 \\ M_{\Sigma^{*+}} - M_{\Sigma^+} &= M_{\Xi^{*0}} - M_{\Xi^-} = 202 \text{ MeV}/c^2 \end{aligned}$$

$$\begin{aligned} \frac{K^*}{3K} = \frac{\Delta^{++}}{2p} = \frac{\Sigma^{*+}}{2\Sigma^+} = \frac{\Xi^{*0}}{2\Xi^-} &= 0.231 \pm 0.027 \\ \delta M = -b^{-1} \ln(a_{po}/a_{vd}) &= 209 \pm 17 \text{ MeV}/c^2 \end{aligned}$$

CONCLUSION:

Hyperfine splittings in baryon direct rates reconstructed from the total rates measured at LEP using the Pei model are consistent with expectations from the baryon mass formula

Hyperfine Splitting between Meson Rates

Hyperfine mass splitting term in mass formula

$$M_{mes} = m_1 + m_2 + A \frac{(\mathbf{S}_1 \cdot \mathbf{S}_2)}{m_1 m_2}$$

for PS-mesons is very large:

-480 MeV/c² for π and -308 MeV/c² for K

This does not agree with relations

$$\frac{\rho}{3\pi} = \frac{\Delta^{++}(1232)}{2p}$$

$$\frac{K^*(896)}{3K} = \frac{\Sigma^{*+}(1385)}{2\Sigma^+} = \frac{\Xi^{*0}(1530)}{2\Xi^-}$$

seen for total rates and direct rates reconstructed with the Pei model

CONCLUSION:

More efforts are necessary for quantitative understanding of the hyperfine splitting in the meson production rates

LEP and Hadronic Reactions

NA27: pp interactions at 400 GeV/c

Normalization:

$$\langle K^{*-}(892) \rangle_{LEP} / \langle K^{*-}(892) \rangle_{NA27}$$

LEP and Heavy Ions

Reasonable consistency between the LEP and hadronic reactions justifies to use the LEP measurements as the reference sample in searches for a possible strangeness enhancement in heavy nuclear collisions, as was already suggested (*Szczekowski, Wilk (1996)*)

Ratios $\langle K_S^0 \rangle / \langle h^- \rangle$ and $\langle \bar{\Lambda} \rangle / \langle h^- \rangle$ at LEP and NA35 for $p + S$, $^{32}S + S$ and $^{32}S + Ag$ collisions at 200 GeV per nucleon

Reaction	$\langle K_S^0 \rangle / \langle h^- \rangle$	$\langle \bar{\Lambda} \rangle / \langle h^- \rangle$
LEP1	0.0962 ± 0.0014	0.0117 ± 0.0006
$p + ^{32}S$	0.067 ± 0.010	0.0086 ± 0.0011
$^{32}S + S$	0.110 ± 0.019	0.022 ± 0.004
$^{32}S + Ag$	0.091 ± 0.011	0.015 ± 0.002

The conclusion about enhanced K_S^0 and $\bar{\Lambda}$ production in $^{32}S + S$ and $^{32}S + Ag$ collisions relative to the production of non-strange particles by a factor of 2 in comparison with nucleon-nucleon and proton-nucleus collisions made by NA35 is far less obvious when these data are compared with the LEP results.

Summary

The origin of Σ^0/Λ , V/P and D/O suppressions is explained by hyperfine splitting.

Σ^0/Λ and D/O suppressions agree with the quantitative expectations from hyperfine mass splittings. More efforts are needed to understand V/PS suppression and relations:

$$\frac{\rho}{3\pi} = \frac{\Delta^{++}(1232)}{2p}, \quad \frac{K^*(896)}{3K} = \frac{\Sigma^{*+}(1385)}{2\Sigma^+} = \frac{\Xi^{*0}(1530)}{2\Xi^-}$$

Strangeness suppression factor

$$\lambda = e^{-(m_s - \hat{m})/T} = 0.295 \pm 0.006$$

is related to the quark mass difference. It is the same for mesons and baryons, with no evidence for additional suppression of the strange baryons.

Important production of several $SU(6)$ baryon multiplets, and especially excited baryons, accounted for in the Pei model but so far neglected in JETSET, is supported by this analysis.

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