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VECTOR-TO-PSEUDOSCALAR AND MESON-TO-BARYON RATIOS IN HADRONIC Z DECAYS AT LEP

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Abstract

Uvarov V.A. Vector-to-Pseudoscalar and Meson-to-Baryon Ratios in Hadronic Z Decays at LEP: IHEP Preprint 2000-47. – Protvino, 2000. – p. 7, figs. 2, tables 1, refs.: 41.

Mass dependences of the total production rates per hadronic Z decay of all light-flavour hadrons measured so far at LEP are extrapolated to the zero mass limit (m=0) using phenomenological laws of hadron production related to the spin, isospin, strangeness content and mass of the particles. The vector-to-pseudoscalar and meson-to-baryon ratios at m=0 are found to be: $\rho^+/\,3\,\pi^+ = 1.2 \pm 0.3$ and $\pi^+/\,p = 2.9 \pm 0.3$, in a good agreement with the predictions of quark combinatorics.

Аннотация

Уваров В.А. Отношения выходов векторных мезонов к псевдоскалярным и мезонов к барионам при адронных распадах Z-бозона на ускорителе LEP: Препринт ИФВЭ 2000-47. – Протвино, 2000. – 7 с., 2 рис., 1 табл., библиогр.: 41.

Зависимости от массы (m) полных выходов на один адронный распад Z-бозона всех измеренных до сих пор на ускорителе LEP адронов с легкими ароматами экстраполируются к нулевому пределу ($m = 0$), используя феноменологические закономерности образования адронов, связанные со спином, изоспином, содержанием странности и массой частицы. В пределе $m = 0$ получены следующие отношения выходов векторных мезонов к псевдоскалярным и мезонов к барионам: $\rho^+/3\pi^+ = 12 \pm 0.3$ и $\pi^+/p = 2.9 \pm 0.3$, которые хорошо согласуются с предсказаниями кварковой комбинаторики.

The measurement of the ratios of particle production rates in e^+e^- annihilation is fundamental relative to the understanding of the fragmentation of quarks and gluons into hadrons. Only phenomenological models, which need to be tuned to the data, are available to describe this hadronization process. In particular, the quark combinatorics model [1,2] predicts the following values for the ratios of the direct production rates of vector and pseudoscalar mesons [1,2] and of mesons and baryons [1]:

$$\rho^+ : \pi^+ = 3 : 1 \qquad \text{and} \qquad \pi^+ : p \, : \, \bar{p} = 3 : 1 : 1. \tag{1}$$

These values originate from the usual spin counting factor $(2J{+}1)$ and from simple combinatorics of $q\bar{q}$, qqq and $\bar{q}\bar{q}\bar{q}$ production. However, the values (1) are not observed experimentally in all types of interactions, at least, in the central kinematical region (see, for example, Refs. [3,4,5]). The fact that the vector-to-pseudoscalar ratio is suppressed relative to the prediction (1) has been known for a long time but is still poorly understood. The comparative properties of meson and baryon production are not completely understood either.

Beyond the cluster fragmentation model [6] and the string model [7], which employ many parameters to describe hadron fragmentation, several attempts were made recently to understand the global properties of particle production in e^+e^- annihilation. In Ref. [8] a similarity in the mass squared dependence of meson and baryon production rates was found. It was followed by rather successful phenomenological models with very few parameters: the "hadron gas model" [9], the "string-based model" [10], the "improved pop-corn model" [11] and the "quark model with constituent quarks" [5].

The purpose of this analysis, presented recently in Refs. [12,13], is to show that relations (1) expected from quark combinatorics are observed experimentally in hadronic Z decays at LEP not for the ratios of the *direct* production rates, but for the ratios of the *"massless"* particle production rates, i.e. for the ratios obtained by extrapolating the empirical mass (m) dependences of the *total* production rates to the zero mass limit m=0.

The total[1] production rates per hadronic Z decay of light-flavour hadrons, used in this analysis (see Appendix), were obtained for at least one state of a given isomultiplet as a weighted average[2] of the measurements of the four LEP experiments: ALEPH [15–17], DELPHI [18–26], L3 [27–30] and OPAL [31–39].

[1] The quoted rates include decay products from resonances and particles with $c\tau < 10$ cm.

[2] In calculating the errors of averages, the standard weighted least-squares procedure suggested by the PDG [14] was applied: if the quantity $[\chi^2/(N-1)]^{1/2}$ was greater than 1, the error of the average was multiplied by this scale factor.

It has been shown that the total production rates per hadronic Z decay of vector, tensor and scalar mesons [40] and of baryons [26] follow phenomenological laws related to the spin (J), isospin (I), strangeness content and mass of the particles. Using the basic idea from Refs. [40,26] and adding the latest data measurements, we analyse the baryon production rates in a way different from the meson production rates. For baryons (Fig. 1a), the sum of the production rates of all states of an isomultiplet is plotted as a function of m^2. In the case where not all states of an isomultiplet is measured at LEP, equal production rates for the other states is assumed. For mesons (Fig. 1b), the production rate per spin and isospin state is plotted as a function of m. This rate was obtained by averaging the rates of particles belonging to the same isomultiplet, excluding charge conjugated states and dividing by a spin counting factor $(2J+1)$. Therefore, the vertical axes of Fig. 1a and 1b are denoted by $(2I+1)\langle n\rangle$ and $\langle n\rangle/(2J+1)$, respectively, where $\langle n\rangle$ is the mean production rate per hadronic Z decay of a given particle.

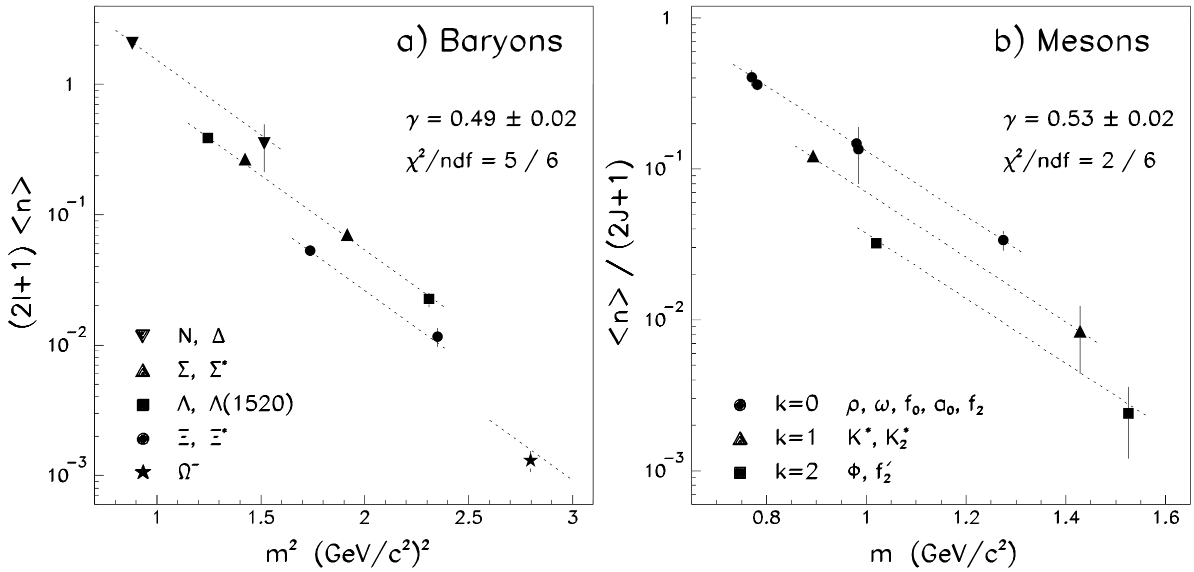

Fig. 1. a) Sum of the baryon production rates of all states of an isomultiplet as a function of the squared baryon mass. b) Meson production rate per spin and isospin state as a function of the meson mass.

It has been shown [26] that the mass dependence of baryon production rates (Fig. 1a) is almost identical for the following sets of particles:

1. N, Δ with strangeness S=0;
2. Σ, Σ^*, Λ and $\Lambda(1520)$ with $|S|$=1;
3. Ξ, Ξ^* with $|S|$=2.

Finally the Ω^- rate is well predicted assuming the same mass dependence with an additional suppression for the higher strangeness ($|S|$=3) equal to that between the first and second or the second and third of the above sets.

A similar simple behaviour is seen (Fig. 1b) for vector, tensor and scalar meson production rates. The mass dependence of these production rates is almost identical for the following sets of particles:

1. ρ, ω, $f_0(980)$, $a_0(980)$, $f_2(1270)$;
2. K^*, $K_2^*(1430)$;
3. ϕ, $f_2'(1525)$.

These sets can be considered as the sets of mesons with the same number (k) of s and $\bar{s}$ quarks in the hadron: k=0, k=1 and k=2 for the 1st, 2nd and 3rd set, respectively. These numbers are close to the well known strangeness contents of mesons [14], except for the $f_0(980)$ meson. The interpretation of the latter is one of the most controversial in meson spectroscopy [41]. The total production rate of $f_0(980)$ was measured with an 8% total error (see Appendix) and in this approach we assume that for the $f_0(980)$, k=0.

The mass dependences of the total production rates of all light-flavour hadrons measured so far at LEP 1 are well fitted by the following formulae:

$$\Sigma_i \, \Sigma_j \, \langle n \rangle_{ij} \;\equiv\; (2I+1) \, \langle n \rangle \;=\; A \, \gamma^k \, \exp\left(-b \, m^2\right) \tag{2}$$

and

$$\langle n \rangle_{ij} \;\equiv\; \langle n \rangle \, / \, (2J+1) \;=\; A \, \gamma^k \, \exp\left(-b \, m\right), \tag{3}$$

for baryons and mesons, respectively, where $\langle n \rangle_{ij}$ is the production rate per spin and isospin state. For baryons, $k = |S|$. The values of the fitted parameters A, b and γ are given in Table 1 and the fitted curves (2) and (3) are shown in Figs. 1a and 1b. The result of the fit of Eq. (3) to the pseudoscalar meson production rates is also given in Table 1 (not shown in Fig. 1b). The pseudoscalars used are the π with k=0 and the K, η, η' with k=1. The quark contents (k=1) of the η and η' mesons originate from the singlet-octet mixing angle, $\theta \approx -10°$, given in Table 13.3 of PDG [14]. The strangeness suppression factor γ is found to be the same within errors for all hadrons (Table 1), with an average value of $\gamma = 0.51 \pm 0.02$, in a good agreement with theoretical expectation [3].

Table 1. Values of the fitted parameters A, b, γ and χ^2 per degree of freedom (b in $(\mathrm{GeV}/c^2)^{-2}$ for baryons and in $(\mathrm{GeV}/c^2)^{-1}$ for mesons).

Particles		A	b	γ	χ^2/ndf
Baryons	(B)	21.4±1.7	2.64±0.08	0.49±0.02	4.6 / 6
Vectors, Tensors, Scalars	(V, T, S)	18.6±4.3	4.95±0.26	0.53±0.02	2.2 / 6
Pseudoscalars	(P)	15.0±1.2	3.85±0.57	0.48±0.10	0.6 / 1

If the production rates are weighted by a factor γ^{-k}, a "universal" mass dependence is observed [26] for all baryons (Fig. 2a). But for mesons (Fig. 2b) there are two different mass dependences; one for vector, tensor and scalar mesons [40] and another for pseudoscalar mesons [12,13]. The curves in Fig. 2b show the result of the fit of Eq. (3) to all meson production rates with the same values of A and γ, but with different values of b. The observed splitting of the mass dependence of meson production rates into two (Fig. 2b) can probably be explained by the influence of the spin-spin interaction between the quarks of the meson (the spins of quarks are parallel for vector, tensor and scalar mesons and anti-parallel for pseudoscalar mesons). However, there is no influence of the value and orientation (with respect to the net spin) of the orbital angular momentum of the quarks, i.e. of the spin-orbital interaction of the quarks (see Figs. 2a and 2b).

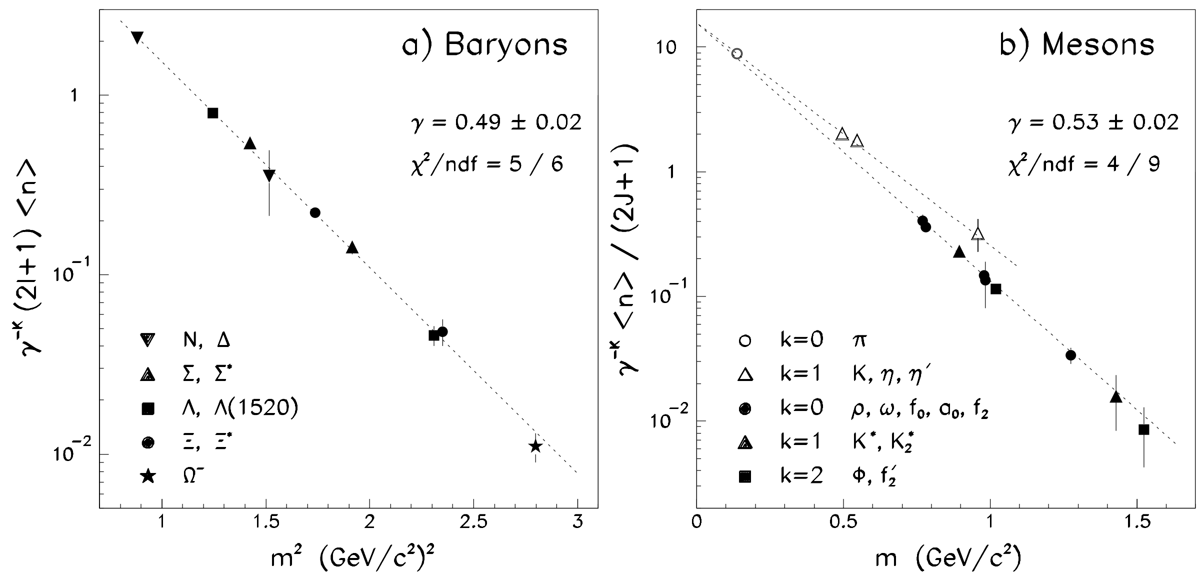

Fig. 2. a) Sum of the baryon production rates of all states of an isomultiplet weighted by a factor γ^{-k} as a function of the squared baryon mass. b) Meson production rate per spin and isospin state weighted by a factor γ^{-k} as a function of the meson mass.

Using the values of the fitted parameter A (given in Table 1), the mass dependences of the vector-to-pseudoscalar and meson-to-baryon ratios can be extrapolated to the zero mass limit m=0, yielding:

$$\frac{\rho^+}{3\,\pi^+} = \frac{A_{V,T,S}}{A_P} = 1.2 \pm 0.3 \quad \text{and} \quad \frac{\pi^+}{p} = 4 \cdot \frac{A_M}{A_B} = 2.9 \pm 0.3, \tag{4}$$

where $A_M = 15.3 \pm 1.2$ is the weighted average of $A_{V,T,S}$ and A_P. Factor 4 in Eq. (4) takes into account the fact that the baryon production rates fitted by Eq. (2) include charge conjugated states and an isospin counting factor $(2I{+}1)$. The results (4) agree with the quark combinatorics model predictions (1), although the latter are expected to be correct only for the directly produced hadrons.

In conclusion, using the mass dependences of the *total* production rates per hadronic Z decay of all light-flavour hadrons measured so far at LEP, we have shown that the $\rho:\pi$ and $\pi:p$ ratios of *"massless"* particle production rates, obtained by extrapolating the empirical mass dependences (2) and (3) to the zero mass limit m=0, are given by the same spin counting and quark combinatorics factors (1) which are assumed in the quark combinatorics model for *direct* hadron production. The slope splitting, observed for the dependence (3) and probably related to the spin-spin interaction between the quarks of the meson, and the difference between the m^2 and m terms in Eqs. (2) and (3) lead to the violation of the vector-to-pseudoscalar and meson-to-baryon relations (1) at real mass values ($m \neq 0$).

Also the ratio of the reduced (by a spin counting factor) rates of "massless" meson (M) and baryon (B) production can be written as:

$$M : B \;=\; \frac{\langle n_M \rangle}{(2J_M+1)} : \frac{\langle n_B \rangle}{(2J_B+1)} \;=\; C \cdot \lambda_{QS} \cdot \gamma^{k_M - k_B}, \tag{5}$$

where $C = 2A_M/A_B$ and $\lambda_{QS} = (2J_B + 1)(2I_B + 1)$. If $C = \frac{3}{2}$, Eq. (5) coincides with relation (1) for the $\pi : p$ ratio. The factor λ_{QS} is an additional suppression factor. Eq. (5) suggests that one "arbitrary unit" of the production rate is given to each state of each meson *(boson)* isomultiplet, but to each baryon *(fermion)* isomultiplet taken as a whole. Therefore, the λ_{QS} can be interpreted as a fermion suppression factor originating from *quantum statistics* properties of bosons and fermions.

The coincidence of the ratios *observed* for the "massless" particles and *expected* for the direct ones can probably be explained by the absence of decay processes at zero masses. However, it is not clear to us whether it is possible to find similar relations for the directly produced hadrons.

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Appendix

Table: Values of the total production rates per hadronic Z decay of light-flavour hadrons obtained by averaging the measurements of the four LEP experiments (A = ALEPH, D = DELPHI, L = L3, O = OPAL) using the standard PDG [14] procedure: if the quantity $F = [\chi^2/(N-1)]^{1/2}$ was greater than 1, the error of the average was multiplied by this scale factor. The rates given include decay products from resonances and particles with $c\tau < 10$ cm. The K^0, K^{*0}, K_2^{*0} and baryon rates include charge conjugated states. The K_2^{*0} rate measured by OPAL [35] for $x_E < 0.3$ was extrapolated in Ref. [25] to the full x_E range.

Particle	Averaged rate	Experiments	F	References
π^0	9.43±0.37	ADLO		[15,21,27,39]
$\pi^\pm$	17.06±0.24	ADO		[16,24,32]
K^0	2.041±0.029	ADLO	1.49	[17,19,29,34]
$K^\pm$	2.26 ±0.055	ADO	1.01	[16,24,32]
η	0.94±0.08	LO		[27,39]
η'	0.17±0.05	LO	2.36	[28,39]
ρ^0	1.23±0.10	AD	1.08	[15,25]
$\rho^\pm$	2.40±0.44	O		[39]
K^{*0}	0.754±0.034	ADO		[15,23,35]
$K^{*\pm}$	0.714±0.043	ADO		[15,19,31]
ω	1.084±0.086	ALO		[15,28,39]
ϕ	0.0966±0.0073	ADO	2.37	[15,23,38]
p	1.037±0.040	ADO	1.04	[16,24,32]
Λ	0.388±0.011	ADLO	2.04	[17,20,29,36]
Σ^-	0.082±0.007	DO		[26,37]
Σ^+	0.107±0.010	LO		[30,37]
Σ^0	0.078±0.008	ADLO		[15,22,30,37]
Ξ^-	0.0265±0.0011	ADO	1.23	[15,20,36]
Δ^{++}	0.088±0.035	DO	3.39	[18,33]
$\Sigma^{*\pm}$	0.0468±0.0043	ADO	1.74	[15,20,36]
Ξ^{*0}	0.0058±0.0010	ADO	2.65	[15,20,36]
Ω^-	0.0013 ±0.00024	ADO	1.14	[15,22,36]
$a_0^\pm(980)$	0.27±0.11	O		[39]
$f_0(980)$	0.147±0.011	DO		[25,38]
$K_2^{*0}(1430)$	0.084±0.040	DO	1.81	[25,35]
$f_2(1270)$	0.169±0.025	DO	1.36	[25,38]
$f_2'(1525)$	0.012±0.006	D		[25]
$\Lambda(1520)$	0.0225±0.0028	DO	1.09	[26,36]

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Отношения выходов векторных мезонов к псевдоскалярным и мезонов к барионам при адронных распадах Z-бозона на ускорителе LEP.

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