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Interpretation of the « Energy Crisis » in the J/ψ Hadronic Decay.

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In this paper a model of the hadronic decay of the J/ψ is described. This model has been developed essentially to interpret the anomalous neutral component (1,2) of this decay. Finally we achieve a scheme coherent with the experimental data known up till now making the hypothesis of a connection between the J/ψ and the η, η′ mesons, so that

$$\frac{(J/\psi \to \eta X)}{(J/\psi \to \text{all})} \simeq 36\% \, .$$

This hypothesis has already been advanced (3) to interpret, beyond the anomalous charged/neutral ratio in the J/ψ hadronic decay (1), other anomalous data, like the relatively aboundant decay $\psi' \to \eta J/\psi$ or the η' mass.

The relative abundance of the radiative decays $J/\psi \to \eta(\eta')\gamma$ (4) corroborates the afore-mentioned connection. Preliminary results of our model have already been reported (5).

In ref. (1) the ratio has been measured between the mean number of charged particles and π^0 produced in the J/ψ hadronic decay:

$$\frac{\langle c^\pm \rangle}{\langle \pi^0 \rangle} = 1.2 \pm 0.4 \, , \tag{1}$$

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(1) R. Baldini Celio, M. Bozzo, G. Capon, R. Del Fabbro, M. Grilli, E. Iarocci, M. Locci, C. Mencuccini, G. P. Murtas, M. A. Spano, M. Spinetti, V. Valente, C. Bacci, G. Penso and B. Stella: *Phys. Lett.*, **58** B, 471 (1976).

(2) W. Bartel, P. Duinker, J. Olsson, D. Pandoulas, P. Steffen, J. Heintze, G. Heinzelmann, R. D. Heuer, R. Mandhenke, H. Riesenberg, A. Wigner and A. H. Walenta: DESY preprint 76/65 (1976).

(3) H. Harari: *Phys. Lett.*, **60** B, 172 (1976).

(4) *a*) W. Bartel, P. Duinker, J. Olsson, D. Pandoulas, P. Steffen, J. Heintze, G. Heinselmann, R. D. Heuer, R. Mundhenke, H. Riesenberg, A. Wagner and A. H. Walenta: DESY preprint 76/65 (1976); *b*) R. Baldini Celio, G. Capon, R. Del Fabbro, G. De Zorzi, E. Iarocci, M. Locci, C. Mencuccini, G. P. Murtas, M. Spinetti, V. Valente, C. Bacci, G. Penso and B. Stella: *Lett. Nuovo Cimento*, **18**, 447 (1977); *c*) W. Bartel, P. Duinker, J. Ollson, P. Steffen, J. Heintze, G. Heinzelmann, R. D. Heuer, R. Mundhenke, H. Rieseberg, B. Schürlein, A. Wagner and A. H. Walenta: DESY preprint 76/40 (1976); *d*) DASP Collaboration: H. U. Martin, *Tblisi Conference* (1976).

(5) B. Jean-Marie: *Rencointre de Moriond* (1976).

where the charged particles are not identified and the mean number of π^0 is obtained by the mean number of observed γ's, in the hypothesis they come essentially from π^0 decays. The quoted error is claimed to be not statistical, but a systematic one.

This result is inconsistent with the J/ψ measured isospin (6), in the absence of electromagnetic effects (aboundant radiative decays or decay of produced η's). In fact it can be shown, using simple isospin considerations (7), that it must be

$$\frac{\langle \pi^\pm \rangle}{\langle \pi^0 \rangle} = 2\,, \tag{2}$$

in a strong decay of a zero-isospin particle, if pions are identified indipendently by other present particles. This conclusion is not altered by the not complete particle identification in ref. (1) and by the presence of the second-order e.m. J/ψ decay (17%) (8). In fact the charged K contribution increases ratio (2)—$\langle K^\pm \rangle / \langle \pi^\pm \rangle = 9\%$ (9), 14% (10)—, moreover charged and neutral pions coming from K^0_s decays do not alter this ratio, due to K^0_s branching ratios, and analogously for K^0_L, which practically decay far from the apparatus. The second-order e.m. J/ψ decay contiibution can be estimated by the measurement of the ratio between charged and neutral wasted energies for total energies near the resonance (8,11):

$$\frac{\langle E_{\text{ch}} \rangle}{E_{\text{tot}} - \langle E_{\text{ch}} \rangle} \simeq \frac{\langle c^\pm \rangle}{\langle \pi^\pm \rangle} \simeq 1.45\,.$$

This contribution decreases the ratio (2), however it does not compensate the aforementioned K$^\pm$ increase (7).

The « energy crisis » in e$^+$e$^-$ annihilation, at energies unlike the J/ψ mass, is a well-known problem. However only statistical considerations suggest it is an inconsistency also for the isovector component.

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(6) B. Jean-Marie, G. S. Abrams, A. M. Boyarski, M. Breidenbach, F. Bulos, W. Chinowsky, G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, D. L. Hartill, J. A. Kadyk, R. R. Larsen, A. M. Litkr, D. Lüke, B. A. Lulu, V. Lüth, H. L. Lynch, C. C. Morehouse, J. M. Paterson, M. L. Perl, F. M. Pierre, T. P. Pun, P. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci, J. S. Whitaker, F. C. Winkelmann and J. E. Wiss: *Phys. Rev. Lett.*, **36**, 291 (1976).

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(8) A. M. Boyarski, M. Breidenbach, F. Bulos, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie, R. R. Larsen, D. Lüke, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, P. Rapidis, B. Richter, R. F. Schwitters, W. Tanenbaum, F. Vannucci, G. S. Abrams, D. D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, J. A. Kadyk, A. M. Litke, B. A. Lulu, F. M. Pierre, B. Sadoulet, G. H. Trilling, J. S. Whitaker, F. Winkelmann and J. E. Wiss: *Phys. Rev. Lett.*, **34**, 1357 (1975).

(9) W. Braunschweig, H. U. Martin, H. G. Sander, D. Schmtz, W. Sturm, W. Wallraff, K. Berkelman, D. Cords, R. Felst, E. Gadermann, B. Gittelmann, H. Hultschig, P. Joos, W. Koch, U. Kötz, H. Krehbiel, D. Kreinick, W. A. McNeely, K. C. Moffeit, A. Petersen, B. H. Wiik, G. Wolf, W. DeBoer, G. Buschhorn, B. Gunderson, R. Kotthaus, U. E. Kruse, H. Liern, H. Oberlack, K. Pretzl, M. Schliwa, S. Orito, T. Suda, Y. Totsuka amd S. Yamada: *Phys. Lett.*, **63** B, 115 (1976).

(10) G. J. Feldman: SLAC PUB 1624 (1975).

(11) J. E. Augustin, A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie, R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, R. F. Schwitters, F. Vannucci, G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. H. Hollebeek, J. A. Kadyk, G. H. Trilling, J. S. Whitaker and J. E. Zipse: *Phys. Rev. Lett.*, **34**, 764 (1975).

A simple interpretation of the experimental value (1) in the J/ψ decay is a significative η production, whose e.m. decays have an abundant neutral component.

To explain the experimental value (1) on the basis of the quoted numbers it would need (⁷), $\langle\eta\rangle$ being the mean number of produced η's:

$$0.18 \leqslant \frac{\langle\eta\rangle}{\langle c^{\pm}\rangle} \leqslant 0.22 . \tag{3}$$

In ref. (¹²) this conclusion has been also evidentiated.

Concerning the J/ψ coupling with the different mesons the hypothesis has been widely considered that it is a SU_3 singlet, partially supported by experimental data (¹³) and the charm model.

To understand whether this hypothesis is in agreement with the expected value (3) and with the other experimental data known up till now on the J/ψ hadronic decay, we need a model for this decay.

The model we adopt is based on the following hypotheses, which seem the simplest *a priori* which can be done:

a) We assume the branching ratio for J/$\psi \to \mathcal{N}$ hadrons to be proportional to the Lorentz invariant phase space (LIPS) times $N-1$ coupling constants λ_i. Only particles stable from the point of view of strong interactions are considered, namely pseudoscalar-meson octet (the available phase space for nucleons is considered negligible, as corroborated by the experimental data (¹³)).

In such a scheme resonances in the intermediate steps, strongly decaying, are included in the available phase space integration. This approximation is less supported if narrow resonances (η', φ, ω) are present in the intermediate steps.

b) If J/ψ is an SU_3 singlet and the pseudoscalar mesons pure SU_3 octet states, then we assume the same value for the coupling constants:

$$\lambda = \lambda_{\pi^+} = \lambda_{\pi^-} = \lambda_{\pi^0} = \lambda_{\eta} = \lambda_{K^+} = \lambda_{K^-} = \lambda_{K^0} = \lambda_{\overline{K}^0} .$$

c) Different cascades for the J/ψ fireball, allowing the same final state, are considered including the suitable combinatorial factors, kaons are considered in pairs, allowing for strangeness conservation.

Suitable isospin statistical weights (¹⁴) are considered, allowing for a total isospin equal to zero.

d) Afterwards LIPS calculations, weak and electromagnetic decays of K^0_s and η's are considered. $K^{\pm}$ and $\pi^{\pm}$ are considered by the same standard and γ's coming from η's are considered as coming from π^0: using these hypotheses we obtain a treatment similar to the experimental one.

We have imposed this model to reproduce, inside the errors, the topological branching ratios, σ_n, of the decay into n charged particles and the relative π^0's mean multiplicities; so that the obtained results give the ratio between charged and neutral mean multiplicities.

(¹²) G. J. FELDMAN and M. L. PERL: SLAC-PUB (July 1977).

(¹³) B. H. WIIK: DESY preprint 76/52 (1976) and reference therein.

(¹⁴) J. SHAPIRO: *Suppl. Nuovo Cimento*, **18**, 40 (1960).

Further tests on the validity of the model have been done examining the forecasts of the values of some partial branching ratios for several bodies decays, for which the afore-mentioned hypotheses are more reliable (⁶):

$$(4)\qquad 2n\pi^{\pm}\pi^{0}\,,\quad n=2,3,4\,;\quad K^{+}K^{-}4\pi^{\pm}\,;\quad K\bar{K}2\pi$$

and the mean number of $K^{\pm}$ for event (⁹,¹⁰).

Several authors (¹⁵) have developed a thermodynamical model of $e^{+}e^{-}$ annihilation based on analogous hypotheses that we have here considered. In these models a connection is obtained between the coupling constant, λ, and the hadronic matter temperature, T_0.

In particular, in our model we obtain the expression

$$(5)\qquad \lambda(T_0)=\frac{1}{2\pi}\,\frac{1}{T_0}\left[(A^2+2B^2)^{\frac{1}{2}}-A\right]\frac{1}{B}\,,$$

where

$$A=m_\pi K\left(\frac{m_\pi}{T_0}\right)+\frac{\alpha}{3}m_\eta K\left(\frac{m_\eta}{T_0}\right),$$

$$B=\frac{4}{3}\left[m_k K\left(\frac{m_k}{T_0}\right)\right]^2,\qquad \alpha=\lambda_\eta/\lambda\,,$$

and $K(m_i/T_0)$ Hankel modified function of the m_i/T_0 ratio ($i=\pi,\eta,K$).

As a starting point to apply this model to J/ψ hadronic decay we used relation (5) for the constant λ, taking $T_0=160$ MeV, consistent with common literature. Moreover we have made the hypothesis that J/ψ is an SU_3 singlet and the mesons of the pseudoscalar octet SU_3 pure states; therefore as a starting point we have taken $\lambda_\eta=\lambda_{\pi^0}$.

As it is shown in table I, the results we obtained using this hypothesis are not entirely satisfactory, but encouraging to go on with the calculus.

Therefore we decided to take the constant λ as a free parameter for the model; in reality, for convenience in comparisons we still used relation (5), getting every time the corresponding T_0 value. On the other hand the inclusive spectrum in momentum of charged particles only partly agrees (⁹) with a termodynamical spectrum at the limit temperature, $T_0=160$ MeV:

$$(6)\qquad \frac{d\sigma}{dp}=C\frac{p^2}{E}\exp\left[-E/T_0\right].$$

A more reliable starting point for an estimate of λ can be achieved from the experimental value of mean tracks kinetic energy, $\langle T_{\text{track}}\rangle\simeq 300$ MeV (¹⁶). This value, which on the other hand is obtained also using measured mean multiplicities, suggests for a spectrum of type (6) a value $T_0=240$ MeV.

Using this last value for T_0 it is possible to reproduce, inside the errors, experimental values of the charged multiplicites, but not the neutral multiplicities; analogously the partial branching ratios (4) cannot be reproduced. In table I we report as typical values

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(¹⁵) J. ENGELS and K. SHILLING: *Nuovo Cimento*, **17** A, 535 (1973) and references therein.

(¹⁶) R. F. SCHWITTERS: *Stanford Conference* (1975).

$\lambda = 3.0$ and 2.1 (GeV)$^{-2}$ ($T_0 = 240$ and 275 MeV). It must be noted that the value of the charged/neutral ratio is in practice constant ($1.6 \div 1.7$) going from $\lambda = 8.8$ (GeV)$^{-2}$ to $\lambda = 2.1$ (GeV)$^{-2}$. Therefore this value can be assumed as a prediction of the model in the afore-mentioned hypotheses about SU_3.

TABLE I.

T_0 (MeV) α	160 1 (%)	240 1 (%)	275 1 (%)	240 2.5 (%)	Experimental values
σ_2	7.5	23.6	31.3	30.0	32 ± 5 (1)
σ_4	36.0	52.3	52.8	50.2	49 ± 8 (1)
σ_6	42.4	22.1	14.6	18.2	18 ± 3 (1)
σ_8	13.1	1.6	0.6	1.3	1 ± 0.6 (1)
$\langle\pi^0\rangle_2$	5.2	3.7	3.3	4.3	3.6 ± 0.9 (1)
$\langle\pi^0\rangle_4$	3.7	2.3	1.9	2.8	3.1 ± 0.7 (1)
$\langle\pi^0\rangle_6$	2.5	1.5	1.3	1.9	2.3 ± 0.6 (1)
$4\pi^\pm 1\pi^0$	0.8	6.1	7.8	4.2	4.0 ± 1.0 (6)
$6\pi^\pm 1\pi^0$	5.8	5.1	3.1	2.8	2.9 ± 0.7 (6)
$8\pi^\pm 1\pi^0$	4.3	0.4	0.1	0.2	0.9 ± 0.3 (6)
$K^+K^-\pi^+\pi^-$	0.01	0.3	0.5	0.2	0.7 ± 0.2 (12)
$K^+K^-4\pi^\pm$	0.2	0.6	0.5	0.4	0.3 ± 0.1 (12)
$K^\pm$/ev	7.0	14.9	17.2	10.9	8.9 ± 1.0 (8); 14 ± 2 (10)
$\langle n^\pm\rangle$	5.3	4.0	3.7	3.8	3.8 ± 0.3 (12)
$\langle\pi^0\rangle$	3.0	2.4	2.3	3.1	3.1 ± 0.8 (1)
$\langle n^\pm\rangle/\langle\pi^0\rangle$	1.75	1.64	1.62	1.23	1.2 ± 0.4 (1)

At this point of the calculus we assumed that the anomalous neutral component of the J/ψ is produced by an excess of η's mesons, taking $\lambda_\eta = \alpha\lambda_\pi$. In the spirit of our model it may naturally be caused by the fact that both η and (or) η′ (which in 70% of events decays into η) are made up of other quarks besides those belonging to SU_3.

The obtained results for $\alpha = 2.5$ and $\lambda = 2.7$ (GeV)$^{-2}$ are also shown in table I.

The contribution of the J/ψ decay via γ could be introduced, in a first approximation, comparing the annihilation outside the resonance with our statistical model using $\lambda \simeq 2$ (GeV)$^{-2}$ and $\alpha \simeq 1$. As it can be seen charged/neutral ratio is reproduced, the charged and neutral multiplicities are in good agreement with the measured values. The comparison with partial channels (4) can be considered satisfactory. In the same way the comparison with the mean number of K$^-$ for event is satisfactory; the anomalous production of η's in the J/ψ decay decreases the K fraction in hadrons, as it was forecast in ref. (3), compared with the expected fraction outside the resonance.

In table II we report results concerning the percent of the η's mesons for the different values we considered of the parameters α and λ. For $\lambda = 2.7$ (GeV)$^{-2}$ and $\alpha = 2.5$ the ratio between the mean number of η's and the mean number of charged particles is then $\langle\eta\rangle/\langle c^\pm\rangle = 0.19$, in agreement with the estimate (3) before given of this ratio. Anal-

TABLE II.

T_0 (MeV) α	160 1 (%)	240 1 (%)	275 1 (%)	240 2.5 (%)
$\sigma_2(\eta+x)$	2.3	7.3	9.5	13.4
$\sigma_2(2\eta+x)$	0.5	1.8	2.1	7.8
$\sigma_4(\eta+x)$	8.3	11.6	10.8	17.6
$\sigma_4(2\eta+x)$	1.0	1.8	1.9	7.5
$\sigma_6(\eta+x)$	7.1	4.5	3.2	5.9
$\sigma_6(2\eta+x)$	0.6	0.6	0.5	2.3
η/ev	24.3	32.5	33.0	73.0

ogously the model furnishes, taking into account the leptonic, the second-order e.m. decays and the small fraction, here neglected, of radiative decays and decays with neutrons of the J/ψ (13):

$$\frac{\Gamma(J/\psi \xrightarrow{\text{dir}} \eta X)}{\Gamma(J/\psi \to \text{all})} \simeq 36\% \,.$$

It must be noted how a nonnegligible number of η's is however required to explain the experimental value of the branching ratio for the decay into 2 charged particles and any number of neutral particles, $(32 \pm 5\%)$ as regards to what was obtained $(\leqslant 10\%)$, adding the identified decay channels (13).

In conclusion we confirm that a scheme coherent with the experimental data, known up till now, on J/ψ hadronic decays is achieved, making the hypothesis of an abundant production of η's. Evidence for this may be pointed out by measuring the spectrum of invariant masses $\gamma\gamma$, of the photons produced in the J/ψ hadronic decays, if opportune cuts on energies and on relative photons angles are used, so that the $\eta \to \gamma\gamma$ decay is well emphasized.

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