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Experimental Study of Hadron Inclusive Production in J/ψ Energy Region

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The mean multiplicities of mesons $\pi^{\pm}$, π^{0}, $K^{\pm}$, K_S^0, ρ^0, K^{*0}, $K^{*\pm}$, and ϕ and baryons p, $\Xi^{\pm}$, and $\Sigma^{\pm}$ (1385) are measured for the first time at J/ψ region with 200,000 events collected at the BEPC with the BES detector. The results are compatible with LUND and Shandong phenomenological models. Based on the experimental results, the strangeness suppression factor s/u and spin suppression factor V(V + P) can be calculated to be ~0.3 and ~0.3–0.5, respectively, which are in good agreement with those given by the ARGUS Collaboration in the Υ region. This indicates that the *SU*(6) breaking is consistent in the energy region from J/ψ to Υ.

Key words: inclusive production, event selection, invariant mass, phenomenological model.

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1. INTRODUCTION

Fragmentation of quarks and gluons into hadrons is a fundamental problem in particle physics. At present, the understanding of this non-perturbative QCD process can only be gradually approached by comparing the predictions of various phenomenological models with the results of inclusive experiments.

In medium and high energy regions, many collaborations, such as ARGUS, TPC, ALEPH, DELPHI, etc., have completed a lot of research work and given the results of hadrons inclusive yields from the 10–90 GeV region [1–3]. Especially, from 1988 to 1992, the ARGUS Collaboration systematically reported the inclusive yields of many baryons and mesons, studied baryon flavor correlations of $p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Xi\Lambda$ and $\Lambda\Lambda'(1520)$, found the *SU*(6) breaking in hadron productions, and observed the enhanced baryon rate in direct Υ decays in comparison with the e^+e^- continuum. The *SU*(6) breaking is often indicated by two parameters: the strangeness suppression factor s/u and the spin suppression factor V(V + P). Different collaborations gave basically consistent results on the measurements of these two factors, which are around 0.3 [3, 4].

On the other hand, the experimental results on hadron inclusive production in the low energy region are in great shortage. Only few results were published more than ten years ago: the DASP Collaboration reported the inclusive yields and momentum spectra of π, K, and p in J/ψ and ψ' decay in 1976 [5], and the ADONE collaboration measured the multiplicities of $\pi^{\pm}$ and π^{0} in the final states of the process J/ψ(3100)→h's in 1975 [6]. Until now, the experimental results of hadron inclusive production in J/ψ region are still far from sufficient.

In theory, to explain the hadronization mechanism of quarks and gluons, many phenomenological models, e.g., LUND, Webber, and Caltech, have been presented. Comparatively, the LUND model [7] agrees better with experiments qualitatively and has been adopted widely. The Theoretical Particle Physics Group of Shangdong University also created its own hadronization model, called the "Shandong Model" [8, 9], which has succeeded in explaining the experimental results (especially the baryon yields) in the Υ energy region.

In this paper, using the data collected at the BEPC with the BES detector [10], we extended the study of hadron inclusive production to the low energy region, presented the inclusive yields of a series of mesons and baryons in the J/ψ region, and made comparisons with phenomenological models. It will be helpful for us to understand the hadronization mechanism better both in experiment and in theory.

2. SELECTION OF HADRON EVENTS AND PARTICLE IDENTIFICATION

The data sample we used contains 2×10^5 events. However, the real hadron events from J/ψ's are estimated to account for only half of the whole data set. The background includes cosmic rays, beam-gas events, and noise events, etc. To measure the mean multiplicities of hadrons, event selection should be conducted first to obtain the total number of hadron events.

The rejection method was used in the event selection. The first step was to classify events according to the number of charged tracks (prong number) it contained. Those with more than 2 prongs were accepted as hadron events, but those with less than 2 prongs would be rejected completely, the events loss arising therefrom would be compensated with the Monte Carlo efficiency correction.

Among the 2-prong events, the background events from Bhabha, di-muon, J/ψ lepton decay, and cosmic rays were eliminated one by one. The detailed selection curves are described in Refs. [11, 12]

A total of 9×10^4 hadron events were selected from the event sample, after efficiency correction, which was done using the LUND Model generator and the BES detector simulation package SOBER, the number of hadron events under analysis was determined to be 115,293. As the efficiency is to a certain extent model dependent, a real data sample selected from the $\psi' \rightarrow \pi^+\pi^- J/\psi$ decay channel was also used to calculate the efficiency [13, 14]. The results from these two methods coincide with each other within 10%. Considering the error originated from other factors, such as the event selection cuts, the error of total number of hadron events was estimated to be about ± 12%.

Particle identification was carried out by using the general method in BES: π, K, and p were identified by time of flight and dE/dx information, while shower counter and muon counter information were used in electron and muon identification, respectively [2].

3. MEASUREMENT OF HADRON INCLUSIVE PRODUCTION

3.1. Momentum spectra and multiplicities of $\pi^\pm$, $K^\pm$, and p

The momentum spectra of $\pi^\pm$, $K^\pm$, and p in the range of 0.2–1.55 GeV/c, the sensitive region for BES detector, were obtained directly from particle identification (see Fig. 1). A simple formula $E\frac{d\sigma}{dp} \propto e^{-bE}$ had been used to fit the spectra [15] and extrapolate it to a much lower energy region. Finally one can integrate the inclusive spectra to determine the multiplicities of various hadrons (Table 2). The fitting slope b is an important parameter in fragmentation function. From Table 1, one can see that the fitting slope b of $\pi^\pm$ and p are basically in accord with that reported by DASP [5, 6]; as far as $K^\pm$ is concerned, the difference is a little larger.

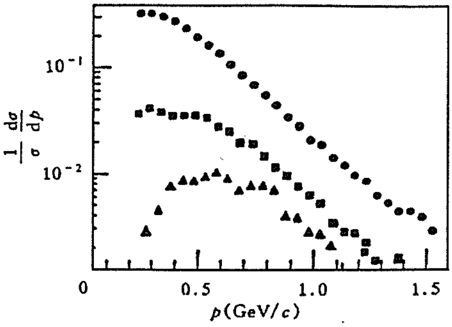

Fig. 1
Momentum spectra of $\pi^\pm$, $K^\pm$, and p.
• π, ■ $K^\pm$, ▲ p.

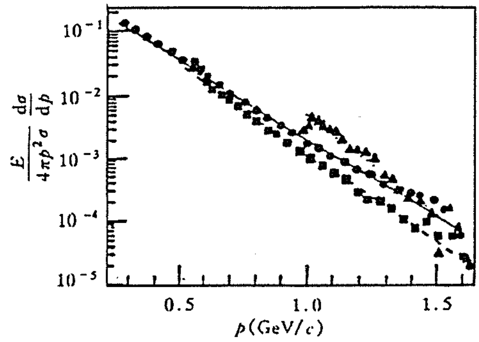

Fig. 2
Scaling cross section of $\pi^\pm$, $K^\pm$, and p.
• π, ■ $K^\pm$, ▲ p.

Table 1

Fitting slope for momentum spectra of $\pi^\pm$, $K^\pm$, and p.

$\sqrt{S}$ (GeV)	$\pi^\pm$	$K^\pm$	$p+\bar{p}$
4–5.2(DSAP)	5.0 ± 1.0	4.9 ± 0.2	5.4 ± 0.5
3.1(DSAP)	5.9 ± 0.1	5.2 ± 0.3	7.2 ± 0.6
3.1(BES)	5.9 ± 0.3	6.7 ± 0.4	7.5 ± 0.6

3.2. Inclusive measurement of hadron resonances

The inclusive yields of hadron resonances were obtained through fitting the invariant mass spectra of their decay products.

The π^0 signal in the invariant mass spectrum of two photons is shown in Fig. 3. To suppress the background and keep the ratio of signal to noise as high as possible, a total deposited energy cut of two photons in a shower counter $(E_1 + E_2) > 0.8$ GeV was required.

K_S^0 signal can be seen in $\pi^+\pi^-$ invariant mass spectrum (Fig. 4). According to a long lifetime characteristic of K_S^0, selection cuts were chosen as follows:

(1) There are more than two charged tracks per event.

(2) After particle identification, at least two charged tracks are considered as π's per event.

(3) Every acceptable $\pi^+\pi^-$ combination should satisfy following three conditions:

1) In the xy plane, the distance from the primary vertex to a crossing point of two tracks (i.e., a secondary vertex) L_{xy} is larger than 0.5 cm.

2) The difference of z coordinates of the two tracks at the secondary vertex $|\Delta z|$ is smaller than 2.5 cm.

3) The direction of total momentum of two tracks at the secondary vertex is in accordance with that connecting the primary vertex and secondary vertex.

Similar analyses were performed for ρ^0, K^{*0}, $K^{*\pm}$, ϕ, $\Xi^\pm$, and $\Sigma^\pm(1385)$ signals (see figs. 5–9). The detailed selection cuts can found in Ref. [12].

Performing the Breit-Wigner fit [16] to the resonance peaks in invariant mass distributions, the number of particles can be calculated. Selection efficiency was obtained by the Monte Carlo simulation. To evaluate the systematic error of efficiency associated with different models, the LUND model generator and the Shandong model generator were used in simulation, respectively. Other

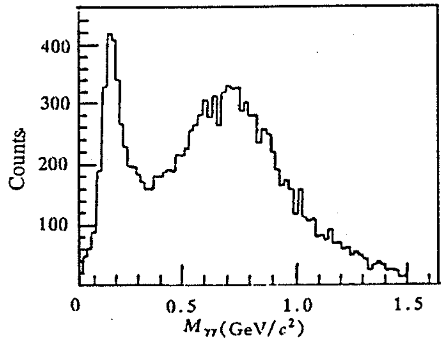

Fig. 3
π^0 signal in $\gamma\gamma$ invariant mass distribution.

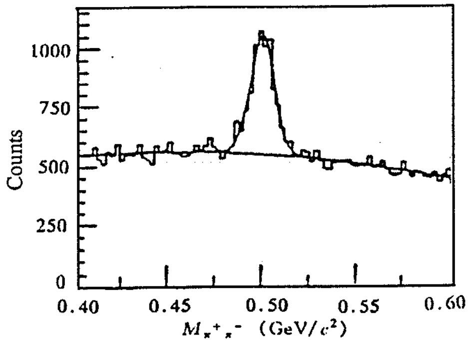

Fig. 4
K_S^0 signal in $\pi^+\pi^-$ invariant mass distribution.

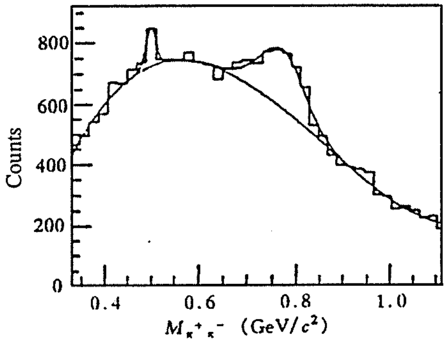

Fig. 5

ρ^0 signal in $\pi^+\pi^-$ invariant mass distribution.

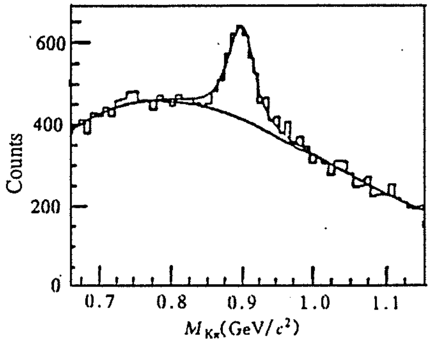

Fig. 6

K^{*0} signal in $K\pi$ invariant mass distribution.

systematic error sources include the error of total number of hadron events 12%, the error from selection cuts, and the uncertainly of particle identification. At the J/ψ resonance region, the cross section of $e^+e^- \to h$'s continuum process accounts for less than 1% of $J/\psi \to h$'s process, and the cross section of hadron production in e^+e^- collision due to the two-photon process is even much smaller, so they were negligible in our analyses. The statistical error mainly came from the Breit-Wigner resonance peak fit (BWFIT). The final results of multiplicities of hadrons are shown in Table 2.

Figure 10 is the inclusive spectrum of K_S^0 as a function of the scaled energy XE. $XE = 2E\sqrt{S}$, where E is the energy of particle and $\sqrt{S}$ is the total energy of the center of mass system. The differential cross section is written in the form of $\frac{1}{\beta \cdot \sigma_h} \cdot \frac{d\sigma}{dx}$, which is the normalized scale-invariant cross section, where σ_h is the total cross section of J/ψ decay into hadrons and X is the scaled energy.

4. RESULTS AND COMPARISON WITH MODEL PREDICTIONS

The measurement of mean multiplicities of hadrons are summarized in Table 2, the predictions of LUND and Shandong models are also listed.

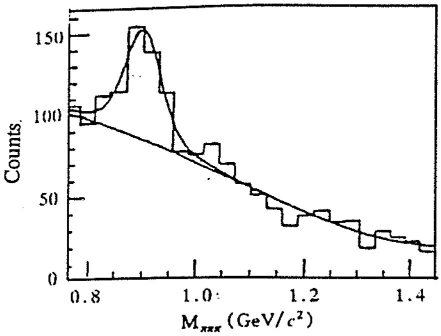

Fig. 7

$K^{*\pm}$ signal in 3π invariant mass distribution.

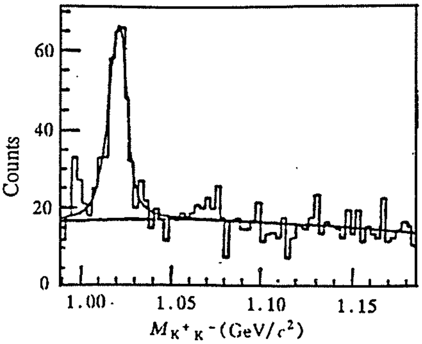

Fig. 8

ϕ signal in K^+K^- invariant mass distribution.

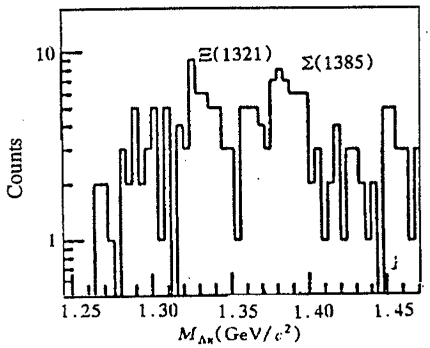

Fig. 9
$\Xi^{\pm}$ and $\Sigma^{\pm}$(1385) signals in $\Lambda\pi$ invariant mass distribution.

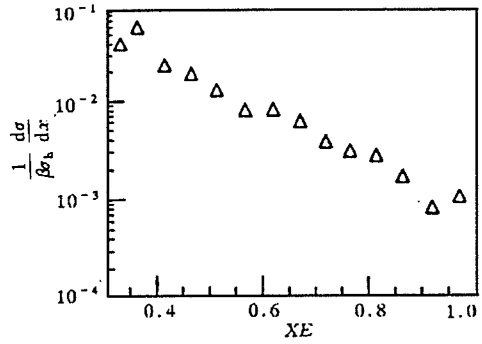

Fig. 10
Energy spectrum of K^0_S.

4.1. Strangeness suppression and spin suppression

Based on the hadron mean multiplicities, we can calculate out the strangeness suppression factor s/u and spin suppression factor V(V + P), which describe the *SU*(6) breaking in the hadronization. In the Υ region, the ARGUS Collaboration presented these parameters as follows:

$$
\begin{aligned}
s/u &= 0.29 \pm 0.06(K^*/2\rho^0); & V/(V+P) &= 0.39 \pm 0.08(\rho/\pi);\\
&= 0.27 \pm 0.08(K/\pi); & &= 0.40 \pm 0.05(K^*/K).\\
&= 0.26 \pm 0.16(2\phi/K^*). & &
\end{aligned}
$$

What should be noted is that the mean multiplicities of various hadrons given in Table 2 correspond to the overall effect of J/ψ decay including unstable particle's secondary decays, but the number of hadrons directly produced from J/ψ decay is needed to calculate s/u and V(V + P) factors. So we used the JETSET generator as a correction and finally came up with our results in J/ψ region as follows:

$$
\begin{aligned}
s/u &= 0.29 \pm 0.15(K^{*\pm}/2\rho^0);\\
&= 0.28 \pm 0.11(K^{*0}/2\rho^0);\\
&= 0.40 \pm 0.19(2\phi/K^{*\pm});\\
&= 0.41 \pm 0.13(2\phi/K^{*0});\\
&= 0.25 \pm 0.05(K^{\pm}/\pi^{\pm});\\
&= 0.33 \pm 0.04(K^0_S/\pi^0).\\
V/(V+P) &= 0.35 \pm 0.11(\rho^0/\pi^0);\\
&= 0.37 \pm 0.18(K^{*\pm}/K^{\pm}).
\end{aligned}
$$

Our results are in good agreement with those of ARGUS. This indicates that the *SU*(6) breaking exists not only in medium and high energy regions but also in low energy regions as well.

4.2. Comparison with model predictions

The LUND model and the Shandong model were put forward initially for the high energy jet events, later they succeeded in explaining the gluon fragmentation mechanism in the Υ region. At

Table 2
Mean multiplicities of hadrons in the J/ψ energy region.

Particles	BES	Shandong model	Lund 7.3
$\pi^+ + \pi^-$	3.02 ± 0.45	3.04	2.93
$K^+ + K^-$	0.39 ± 0.08	0.32	0.35
π^0	1.59 ± 0.22	1.70	1.65
ϕ	0.020 ± 0.005	0.025	0.026
ρ^0	0.198 ± 0.063	0.279	0.277
K_s^0	0.120 ± 0.018	0.157	0.171
$K^{*0} + \bar{K}^{*0}$	0.097 ± 0.025	0.142	0.170
$K^{*+} + \bar{K}^{*-}$	0.100 ± 0.043	0.141	0.172
$p + \bar{p}$	0.11 ± 0.03	0.101	0.136
$\Xi^- + \bar{\Xi}^+$	0.0041 ± 0.0012	0.0043	0.0029
Σ^- (1385) = $\bar{\Sigma}^+$(1385)	$(2 \pm 1.5) \times 10^{-3}$	0.00237	0.002
Σ^+ (1385) = $\bar{\Sigma}^-$(1385)	$(2 \pm 1) \times 10^{-3}$	0.00244	0.0018

present, theorists are very concerned about their feasibility in a lower energy region such as J/ψ. From our measurements shown in Table 2, one can see that model predictions approach closely the experimental results, especially in some cases like $\pi^\pm$, $K^\pm$, π^0, ϕ, and p, the mean multiplicities from models and experiments agree with each other within 1 standard deviations. This indicates that the phenomenological models are feasible after being extended to the low energy region, and their predictions are compatible with experiments. However, to test precisely the different phenomenological models, further experimental studies are needed, especially on the spectra, flavor correlation, and rapidity correlation, which are sensitively model dependent.

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REFERENCES

[1] H. Albercht *et al.*, (ARGUS), *Z. Phys.*, **C39**(1988), p. 177; **C41**(1989), p. 557; **C44**(1989), p. 547; **C46**(1990), p. 15; H. Albercht *et al.*, (ARGUS), *Phys. Lett.*, **236B**(1990), p. 102; **230B**(1989), p. 349, **215B**(1988), p. 429.

[2] P. Avery *et al.*, *Phys. Rev.*, **D43**(1991), p. 3599, **D31**(1985), p. 2161.

[3] A. De Angelis CERN PPE/93-35(1993); ALEPH note (PHYSIC 92-107).

[4] W. Hofmann, *Ann. Rev. Nucl. Part. Sci.*, **38**(1988), p. 279.

[5] W. Braunschweig *et al.*, *Phys. Lett.*, **B63**(1976), p. 115.

[6] R. Baldini-Celio *et al.*, *Phys. Lett.*, **B58**(1975), p. 471.

[7] B. Anderson *et al.*, *Phys. Rep.*, **97**(1983), p. 31; X. Artru, *Phys. Rep.*, **97**(1983), p. 147; A. Casher, H. Neuberger, and S. Nussinov, *Phys. Rev.*, **D20**(1979), p. 179; **D21**(1980), p. 1966.

[8] Tian Lili and Xie Qubing, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **17**(1993), p. 885.

[9] Lili Tian *et al.*, *Phys. Rev.*, **D49**(1994), p. 4517; Qubing Xie *et al.*, *Phys. Rev.*, **D38**(1988), p. 2169.

[10] J.Z. Bai *et al.*, *Nucl. Inst. Meth.*, **A344**(1994), p. 319; Bai Jingzhi *et al.*, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **16**(1992), p. 769.

[11] Bai Jingzhi *et al.*, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **19**(1995), p. 673.
[12] Zhao Xin, "The Experimental Study of Hadron Inclusive Production in J/ψ Energy Region," Ph.D. thesis, Shandong University, 1996.
[13] Yan Changzheng, "The Measurement of the Branching Ratio of J/ψ Leptonic Decay with $\psi(2s) \rightarrow \pi^+\pi^- J/\psi$," thesis, The Institute of High Energy Physics, 1993.
[14] Fang Weizhe, "The Measurement of $\psi(2s)$ Resonance Parameters," thesis, Institute of High Energy Physics, 1995.
[15] Yu Zhitang, "The Study of Hadron Production in J/ψ Decay," thesis, Institute of High Energy Physics, 1995.
[16] Xu Rongsheng, Zhang Xueyao, and Li Qun, "Breit-Wigner Fit," *BES Report*, 1990.