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MEASUREMENT OF HADRONIC PRODUCTION OF THE $\chi_1^{++}(3507)$ AND THE $\chi_2^{++}(3553)$ THROUGH THEIR RADIATIVE DECAY TO J/ψ

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ABSTRACT

The $\chi_1^{++}(3507)$ and the $\chi_2^{++}(3553)$ states have been observed in the Goliath spectrometer at the CERN SPS in 185 GeV/c π^--Be collisions. Their radiative decays contribute 17.7% (for the χ_1^{++}) and 12.8% (for the χ_2^{++}) to J/ψ production. At this energy, their cross-sections are 65 ± 19 nb and 96 ± 29 nb, respectively.

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Using a large-acceptance spectrometer, we have performed an experiment at the CERN Super Proton Synchrotron (SPS) to study dimuon production in π^--Be interactions at 185 GeV/c [1]. One of the major goals of the experiment is to investigate the hadronic production mechanisms of $c\bar{c}$ states. This particular experiment has identified χ states with different quantum numbers. This allows a stringent test of different models of χ production.

In this experiment we have observed radiative decays of χ's into J/ψ's. The photons were observed through their conversion into e^+e^- pairs in a magnetic spectrometer. We present here the result that 30.5 ± 5.0% of J/ψ's come from χ decay. This is lower than the published value of 70 ± 28% measured at 217 GeV/c [2] in a lead-glass calorimeter at FNAL, but is comparable to the ratio of 38% ± 10% measured by using a lead-scintillator calorimeter in association with our own experiment[3]. It is important to note that these two calorimeter determinations were unable to resolve the different χ states. Previously we established that less than 1% of J/ψ's come from $\chi(3554) \to J/\psi + \pi^+ + \pi^- + \pi^0$ [4]. The branching fractions for χ decays into other states containing a J/ψ are thought to be small[5].

Our data sample of 50,037 dimuons in the mass range 2.95 to 3.25 GeV contains 44,750 J/ψ mesons. Our J/ψ mass resolution has a standard deviation of 32 MeV. In calculating effective masses of photons detected in our apparatus with J/ψ mesons, we constrain the J/ψ mass to be 3.097 GeV [*]. Photons are detected by their conversion into e^+e^- pairs. These conversions occur primarily in one of the three beryllium production targets. Altogether, these targets are 0.27 of a radiation length long. Scintillation counters and MWPCs provide 0.04 of a radiation length for additional conversions. The e^+ and e^- momenta are measured in our spectrometer. The γ four-momentum is taken to be the sum of the e^+ and e^- four-momenta, constrained to have zero mass.

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*) We measure the J/ψ mass to be 3098.4 ± 0.2 ± 2.0 MeV, but we use the Particle Data Group value of 3097 MeV for this purpose.

The pattern recognition program separates the e^+e^- pair sample into two classes of events, depending on whether the e^+e^- pair appears to come from a secondary vertex (V^0 events) or from the primary vertex. Figure 1a shows the V^0 mass distribution corresponding to the assumption that the charged tracks are electrons. There is a prominent low-mass γ signal. The peaks at 270 MeV and 400 MeV come from Λ^0 and K^0 decays, respectively. Figure 1b shows the V^0 mass distribution obtained by using the pion mass for the charged tracks. The γ peak appears at 290 MeV, and the K^0 peak now has the appropriate value of 498 MeV. All V^0 events in fig. 1a with a mass less than 60 MeV are taken to be γ's.

In fig. 1c we show the effective mass distribution for pairs of tracks originating from the primary vertex; each track is assumed to be an e^+ or e^- depending on the charge of the track. At low ee masses the opposite-sign combinations (full line) show an excess of events compared with like-sign combinations (dotted line). We interpret this excess as γ rays. From our J/ψ sample a total of 7198 e^+e^- pairs, including background, exists below a cut of 25 MeV for the primary-vertex gammas and 60 MeV for the secondary-vertex gammas. The combined sample is used in the analysis presented here.

A well-defined π^0 peak at the correct mass in the two γ effective mass distribution (fig. 1d) is an illustration of our capability to reconstruct gammas from our J/ψ event sample. The price one pays for this excellent mass resolution is a low γ-detection efficiency of approximately 1%, consistent with the number of observed π^0's.

The J/ψ-γ effective mass distribution is plotted in fig. 2. An excess of events occurs at masses of 3.507 GeV and at 3.553 GeV.

To confirm that these two peaks correspond to the $\chi(3508)$, with $J^{PC} = 1^{++}$, and the $\chi(3554)$, with $J^{PC} = 2^{++}$ (called the χ_1^{++} and the χ_2^{++} for the remainder of the paper) we have calculated our acceptance, efficiency, and mass resolution in a Monte Carlo study. The $\chi(3508)$'s were generated with the same x_F and p_T distributions as that we measure for J/ψ mesons. Isotropic χ decay was assumed.

The simulated e^+e^- pairs coming from conversions, together with $\mu^+\mu^-$ pairs coming from J/ψ decays, have been superimposed on raw data from random experimental events in order to include pattern recognition effects. Electron energy loss was properly taken into account*). In fig. 3 the dotted line shows such a simulated J/ψ-γ mass distribution obtained after processing by our standard event reconstruction program. One peak appears at the generated mass defining our experimental resolution of 7 MeV standard deviation and a global detection efficiency of $1.15 \pm 0.06\%$.

With a binning suggested by the experimental resolution, we fitted the J/ψ-γ mass distribution, assuming two peaks and a background. The background shape was determined by combining J/ψ's with γ's from different events. Table 1 gives the relevant parameters of the fit: the mass, the width, and the number of events in each signal. The corresponding χ masses from the Particle Data Group[6] and the Crystal Ball experiment[7] are also given in Table 1. The mass agreement is excellent and the widths are compatible with our mass resolution. We do not observe a signal at the χ_0^{++} mass of 3.41 GeV, consistent with its low branching fraction into J/ψ-γ [7].

Using the computed efficiency, we can find the percentage of J/ψ mesons produced by χ's. The result is that $17.7 \pm 3.5 \pm 1.5\%$ of the J/ψ mesons come from χ_1^{++} decays and $12.8 \pm 2.3 \pm 1.5\%$ come from χ_2^{++} decays. (The first errors are statistical and the second Monte Carlo statistical errors.)

The χ cross-sections can now be determined using the branching fractions for $\chi_1^{++} \to J/\psi$-γ of $31.5 \pm 5.2\%$ and for the $\chi_2^{++} \to J/\psi$-γ of $15.4 \pm 2.4\%$ [6]. Using a $J/\psi\ \pi^-$ production cross-section of 116 nb **) we find that the cross-sections for χ_1^{++} and χ_2^{++} production are 65 ± 19 nb and 96 ± 29 nb, respectively. We have checked that the number of χ's resulting from ψ' production and decay is negligible.

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*) Most of the electrons from photon conversions see, on average, only few percent of a radiation length.

**) We measured the J/ψ cross-section per nucleon to be 95 nb at 150 GeV/c. From this and J/ψ yields from other experiments, we deduced a total cross-section of 116 nb per nucleon for J/ψ production at 185 GeV/c.

The ratio of the two χ states contribution to J/ψ production, $B \cdot \sigma(\chi_2^{++})/B \cdot \sigma(\chi_1^{++})$ is 0.72 ± 0.25. This ratio is not influenced by our main systematic error, nor by the efficiency, nor by the error on the branching-ratio measurements.

Among the most popular models for χ production, neither the quark-antiquark fusion model[8)], nor the gluon-gluon model[9)], can alone explain the ratio of 0.72 ± 0.25 between the contributions of χ states. In contrast, the so-called "colour evaporation model"[10)] is in agreement with this value[*)].

In summary, owing to an excellent J/ψ-γ mass resolution, we have been able to observe both the χ_1^{++} and χ_2^{++}, as well as to measure the hadron production cross-sections and the contributions to J/ψ production of each χ-state.

*) With a statistical weight $(2J+1)$ production, this model gives $R = 0.81$ if we use the known branching ratios[6)].

Table 1

Results on χ states

	1^{++}	2^{++}	Units
Mass	3507.4 ± 1.7 [a)]	3553.4 ± 2.2	MeV
σ	7.0 ± 1.5	7.1 ± 2.2	MeV
Number of events	91	66	
Percentage of J/ψ from this χ state	17.7 ± 3.5	12.8 ± 2.3	%
Production cross-sections	65 ± 19	96 ± 29	nb
Mass, from ref. 6	3507 ± 4	3551 ± 5	MeV
Mass, from ref. 7	3508.4 ± 0.4 ± 4.0	3553.9 ± 0.5 ± 4.0	MeV
σ, from ref. 7	< 0.12	1.8 ± 0.4	MeV

a) We used a systematic error of 1 MeV on the J/ψ mass: 3097 ± 1 MeV [6).

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7) SLAC Crystal Ball results, for example: M.J. Oreglia, SLAC-236(UC-34d), December 1980. (Note that The Crystal Ball Collaboration uses a J/ψ mass of 3095 MeV/c^2.)

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Figure captions

Fig. 1 : a) V^0 mass distribution with an e^+e^- hypothesis for all events whose $M(\mu^+\mu^-) > 2.8$ GeV.

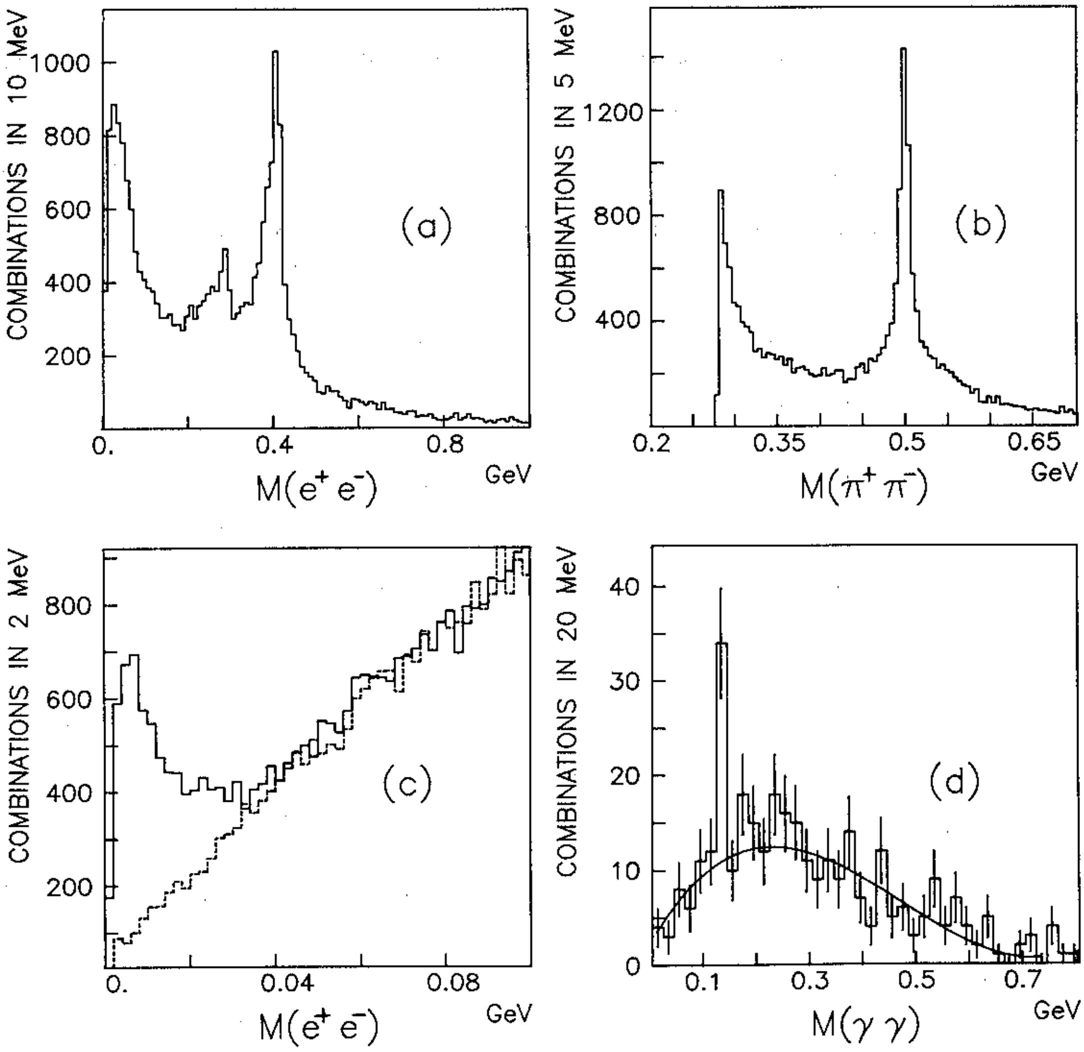
b) V^0 mass distribution with a $\pi^+\pi^-$ hypothesis for all events whose $M(\mu^+\mu^-) > 2.8$ GeV.

c) Effective mass distribution with an e^+e^- hypothesis for pairs of tracks originating from the primary vertex: full line is opposite-sign combination, dotted line is like sign.

d) Two-γ effective mass distribution: full line is a background fit from uncorrelated γ's.

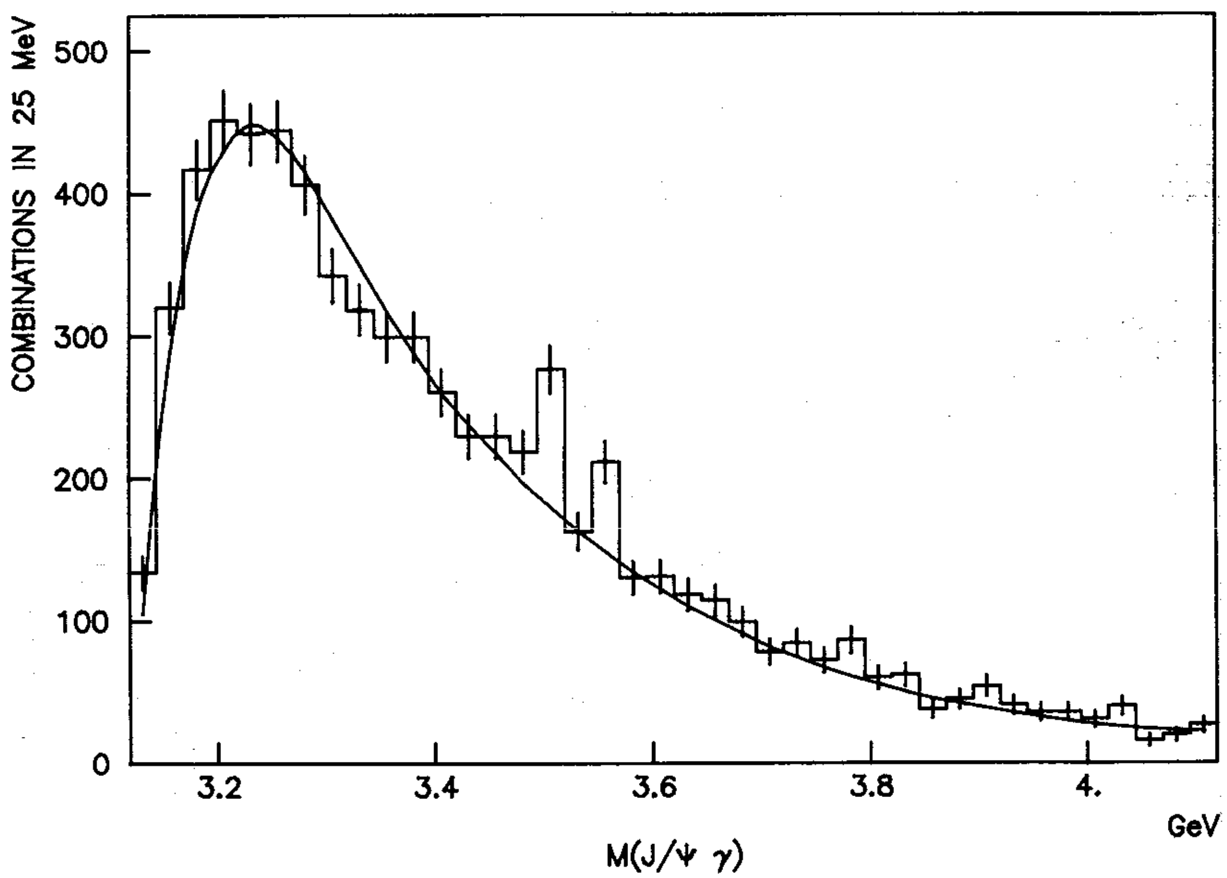
Fig. 2 : J/ψ-γ effective mass distribution where the J/ψ and γ are constrained to 3097 MeV and 0 MeV mass, respectively. Full line is a background estimation by whose the shape was determined by combining uncorrelated J/ψ and γ's.

Fig. 3 : J/ψ-γ effective mass spectrum in the χ region: dotted histogram is a Monte Carlo simulation from a generated $\chi(3508)$ state (see text); full line is a fit of the experimental J/ψ-γ effective mass. (See Table 1 for parameters.) The background parametrization is obtained by fitting uncorrelated J/ψ-γ combinations.



COMBINATIONS IN 10 MeV
1000
800
600
400
200
(a)
0.
0.4
0.8
GeV
M(e+ e-)
COMBINATIONS IN 5 MeV
1200
800
400
(b)
0.2
0.35
0.5
0.65
GeV
M(π+ π-)
COMBINATIONS IN 2 MeV
800
600
400
200
(c)
0.
0.04
0.08
GeV
M(e+ e-)
COMBINATIONS IN 20 MeV
40
30
20
10
0
(d)
0.1
0.3
0.5
0.7
GeV
M(γ γ)

Fig. 1



COMBINATIONS IN 25 MeV
500
400
300
200
100
0
3.2
3.4
3.6
3.8
4.
GeV
M(J/Ψ γ)

Fig. 2

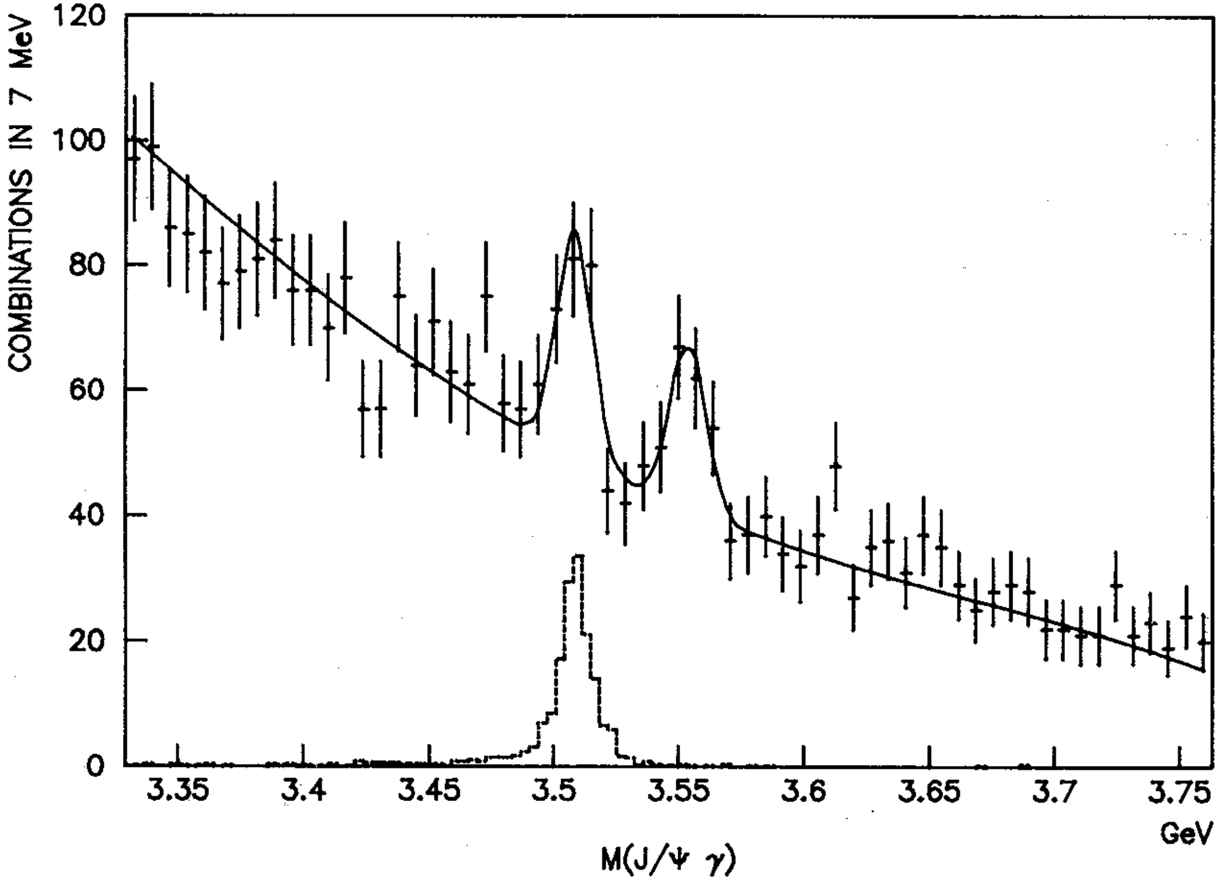

COMBINATIONS IN 7 MeV
120
100
80
60
40
20
0
3.35
3.4
3.45
3.5
3.55
3.6
3.65
3.7
3.75
GeV
M(J/Ψ γ)

Fig. 3