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OBSERVATION OF AN η_c CANDIDATE STATE WITH MASS 2978 ± 9 MeV *

R. Partridge, C. Peck, F. Porter
Physics Department, California Institute of Technology
Pasadena, California 91125

W. Kollmann[a], M. Richardson, K. Strauch, K. Wacker
Lyman Laboratory of Physics, Harvard University,
Cambridge, Massachusetts 02138

D. Aschman, T. Burnett[b], M. Cavalli-Sforza,
D. Coyne, H. Sadrozinski
Physics Department, Princeton University,
Princeton, New Jersey 08544

and

R. Hofstadter, I. Kirkbride, H. Kolanoski[c],
K. Königsmann, A. Liberman[d], J. O'Reilly, J. Tompkins
Physics Department and High Energy Physics Laboratory
Stanford University, Stanford, California 94305

E. Bloom, F. Bulos, R. Chestnut, J. Gaiser,
G. Godfrey, C. Kiesling[e], M. Oreglia
Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94305

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[a]Present address: Wentorfer Strasse 149, 2050 Hamburg, Federal Republic of Germany.

[b]Present address: Physics Department, University of Washington, Seattle, Washington 98195.

[c]Present address: University of Bonn, Bonn, Federal Republic of Germany.

[d]Present address: Schlumberger-Doll Research Center, Ridgefield, Connecticut 06877.

[e]Present address: Max Planck Institute for Physics and Astrophysics, Munich, Federal Republic of Germany.

ABSTRACT

An η_c candidate state has been observed with a mass M = (2978 ± 9) MeV and a natural line width $\Gamma < 20$ MeV (90% C.L.) using the Crystal Ball NaI(Tℓ) detector at SPEAR. Radiative transitions to this state are observed from $\psi'(3684)$ and $J/\psi(3095)$ in the inclusive photon spectra. The branching fraction to this state from the ψ' is (0.43 ± 0.08 ± 0.18)%. In addition, evidence is presented for the decay of this new state into $\eta\pi^+\pi^-$ and an upper limit is presented on the decay into $\pi^0K^+K^-$.

The properties of charmonium have been the subject of intense experimental and theoretical work since the J/ψ and ψ' were discovered more than five years ago. Of particular interest has been the question of the existence, mass and width of the η_c, the 1^1S_0 partner of the 1^3S_1 charmonium state, the J/ψ. Potential models[1] and dispersion relation models[2] indicate that the η_c lies between 20 MeV above and 100 MeV below the J/ψ. In addition, a number of detailed calculations[3] have been made of the expected radiative rates to the η_c from J/ψ and ψ'.

From their first publication, these theoretical predictions have stimulated experimental searches for the η_c. An initial candidate for the η_c state, called X(2830)[4], had a mass lower than theoretically expected. This state was not observed in inclusive photon spectra from the J/ψ; an upper limit[5] was set much below the expected branching fraction[3]. The X(2830) was not confirmed by the Crystal Ball collaboration in a more sensitive experiment[6]; thus the question of the existence of the η_c has remained open.

We have observed a new state with mass M = (2978 ± 9) MeV in radiative decays of the J/ψ and ψ', as well as the decay of this new state into $\eta\pi^+\pi^-$. For the present we call this state the η_c candidate.

The data were obtained using the Crystal Ball NaI(Tℓ) detector[6,7] at the SPEAR e^+e^- storage ring of the Stanford Linear Accelerator Center. Samples of $(8.1 \pm 0.6) \times 10^5$ ψ' and $(7.9 \pm 0.6) \times 10^5$ J/ψ hadronic decays, resulting from integrated luminosities of 1630 nb^{-1} and 323 nb^{-1} respectively, were used in this analysis. The overall geometric and trigger efficiency for hadronic decays is greater than 98%. After removing cosmic rays, beam-gas interactions and QED events, the overall efficiency for detecting hadronic events is (93 ± 5)%, with a residual background of less than 2%.

A number of cuts were applied to obtain inclusive photon spectra[8,9]. Photon showers were required to be entirely contained in the detector and to be well separated from charged particles. Photon pairs that could be reconstructed to a π^0 were removed. Figure 1 shows the inclusive photon spectrum obtained from hadronic decays of the ψ'. The transitions[5,10] to the well-established χ states are indicated in the figure as are the cascade transitions[10,11,12]. Also clearly seen is a signal of greater than five standard deviations at E_γ = (634 ± 13) MeV. The error in the photon energy is primarily systematic, resulting from a ± 2% uncertainty in the absolute NaI(Tℓ) energy calibration. This signal corresponds to a transition to a state of mass M = (2983 ± 16) MeV. Several systematic checks were made to verify that the signal appears uniformly over the solid angle of the apparatus and in the data obtained in the earlier and later parts of the data collection period. These and other consistency checks are discussed in detail elsewhere[9].

If this signal corresponds to the hindered M1 transition[3] $\psi' \rightarrow \gamma\eta_c$, then we expect to observe the transition $J/\psi \rightarrow \gamma\eta_c$. Figure 2 shows the inclusive photon spectrum obtained from hadronic decays of the J/ψ. There appears to be an enhancement about a photon energy of 112 MeV, corresponding to a state of mass $M \sim 2981$ MeV. A simultaneous fit was therefore performed to the mass, M, and natural line width, Γ, of the η_c candidate for both the ψ' and J/ψ signal regions. The two observed signals were fit by a Breit-Wigner line shape convoluted with a Gaussian energy resolution; independent quadratic forms were used for the backgrounds. The Gaussian resolutions (σ = 4.7 MeV at E_γ = 112 MeV and σ = 18.3 MeV at E_γ = 634 MeV) were derived from other Crystal Ball measurements[7].

Figures 3a,b show the best fit obtained, together with the data for the ψ' and J/ψ inclusive spectra respectively, before and after background subtraction. The parameters from the best fit, excepting the primarily systematic error in M, are

$$M = (2981 \pm 15)\ \text{MeV},\ \Gamma = 20^{+16}_{-11}\ \text{MeV},\ \chi^2/\text{ndf} = 53/66 \quad . \tag{1}$$

The significance of a non-zero amplitude for the state obtained from the fit is over five standard deviations. The systematic error in M arises mainly from the energy calibration uncertainty in the ψ' contribution to the fit, and uncertainty in the background shape in the J/ψ contribution; it dominates the ± 2 MeV statistical error. The dependence of χ^2 on Γ is shown in Fig. 4. A broad minimum in χ^2 is observed centered at Γ = 20 MeV. The value of Γ is primarily determined from the J/ψ inclusive spectrum. The error in Γ, shown in (1), is obtained from Fig. 4 and is therefore purely statistical. An additional uncertainty due to the choice of the functional form for the background to the J/ψ signal has not yet been evaluated.

The reconstruction efficiency for a single photon in an inclusive hadronic final state can at present be reliably estimated only for the ψ' decays, where the photon energy is 634 MeV. For the low energy photons from the J/ψ, background sources are much more severe. Using a Monte Carlo estimate of the efficiency, assuming $J^P = 0^-$ for the η_c candidate, we obtain the inclusive branching ratio BR($\psi' \rightarrow \gamma\eta_c$ candidate) = $(0.43 \pm 0.08 \pm 0.18)\%$. The errors shown are statistical and systematic respectively, with the latter dominated by the uncertainty in the photon reconstruction efficiency. The value for the branching ratio compares well with theoretical estimates[3] of 0.2% to 0.4%.

We have also looked for exclusive decays of the η_c candidate into hadrons by performing kinematic fits to exclusive final states with multiple photons and two charged hadrons[13]. The Crystal Ball measures both the energy and angle of electromagnetically showering particles; for charged hadrons (π,K) only the angles are measured well. Secondary interactions of the charged hadrons in the sodium iodide complicate the fitting of some events, but special pattern recognition algorithms have been developed to deal with this effect.

Events with a 3-photon, 2-charged particle topology were selected from the sample of J/ψ hadronic decays and subjected to a three-constraint kinematic fit to the hypothesis

$$J/\psi \to \gamma\eta\pi^+\pi^- \ , \ \eta \to \gamma\gamma \quad . \qquad (2)$$

The energy spectrum for the low energy radiated photon is shown in Fig. 5 for events which pass the fit with a probability of χ^2 greater than 0.10. A clear signal is seen above background. A maximum likelihood fit gives the $\eta\pi^+\pi^-$ mass corresponding to this signal as (2974 ± 2 ± 9) MeV, where the first error is statistical and the second is an estimate of the systematic uncertainty. The mass agrees within errors with the value determined from the inclusive spectra.

The $\gamma\eta\pi^+\pi^-$ data contain additional information on the width of the η_c candidate. Given the limited statistics of this measurement, we choose to combine the $\chi^2(\Gamma)$ function obtained from the likelihood fit to these data with the function shown in Fig. 4. The resulting function provides an upper limit on the natural line width of $\Gamma < 20$ MeV (90% C.L.).

The detection efficiency for the exclusive reaction (2) has been estimated by a Monte Carlo calculation where the η_c was assumed to have $J^P = 0^-$, and to decay with a phase-space distribution. The signal of (18 ± 6) events corresponds to a product branching ratio $BR(J/\psi \to \gamma\eta_c \text{ candidate}) \cdot BR(\eta_c \text{ candidate} \to \eta\pi^+\pi^-) = (3.1 \pm 1.1 \pm 1.5) \times 10^{-4}$, where the errors are statistical and systematic respectively.

The Mark-II collaboration at SPEAR has observed an enhancement in $\psi' \to \gamma\pi^\pm K^\mp K^0_S$ at $M(\pi KK) = (2980 \pm 8)$ MeV [14]. We do not observe a signal in $J/\psi \to \gamma\pi^0 K^+K^-$ in this mass range, with an upper limit of 1.5×10^{-4} (90% C.L.). Comparison of these two results awaits a reliable determination of $BR(J/\psi \to \gamma\eta_c$ candidate).

In summary, an η_c candidate state is observed with mass (2978 ± 9) MeV. This estimate of the mass is obtained by averaging the masses determined from the inclusive and exclusive decays. The error shown is primarily systematic. The upper limit on the width of the state of $\Gamma < 20$ MeV (90% C.L.) is consistent with the value of 5 MeV preferred by quantum chromodynamics theory[3]. Final identification of this state as the pseudoscalar hyperfine partner of the J/ψ will depend on the determination of J^P as 0^-, and approximate agreement between the experimentally measured transition rate from the J/ψ and the value predicted by the charmonium model[1].

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FIGURE CAPTIONS

1. The inclusive photon spectrum from ψ' hadronic decays. Counts are plotted in logarithmic bins since the resolution, $\Delta E/E$, is nearly constant in E for NaI(Tℓ).
2. The inclusive photon spectrum from J/ψ hadronic decays. The structure at $E_\gamma \sim 200$ MeV results from minimum ionizing charged particles which have been misidentified as photons[8,9].
3. Inclusive photon spectra from (a) ψ' and (b) J/ψ decays in the region of the η_c candidate signal, with fit results overplotted (Γ = 20 MeV). Unsubtracted and background subtracted spectra are shown; the background is determined from the fit described in the text.
4. The χ^2 for the best fit to the inclusive spectra as a function of the width assumed for the η_c candidate. The width obtained from lowest order quantum chromodynamics (QCD)[3] is also shown.
5. Fitted energy of the photon for events fitted to the hypothesis $J/\psi \to \gamma\eta\pi^+\pi^-$.

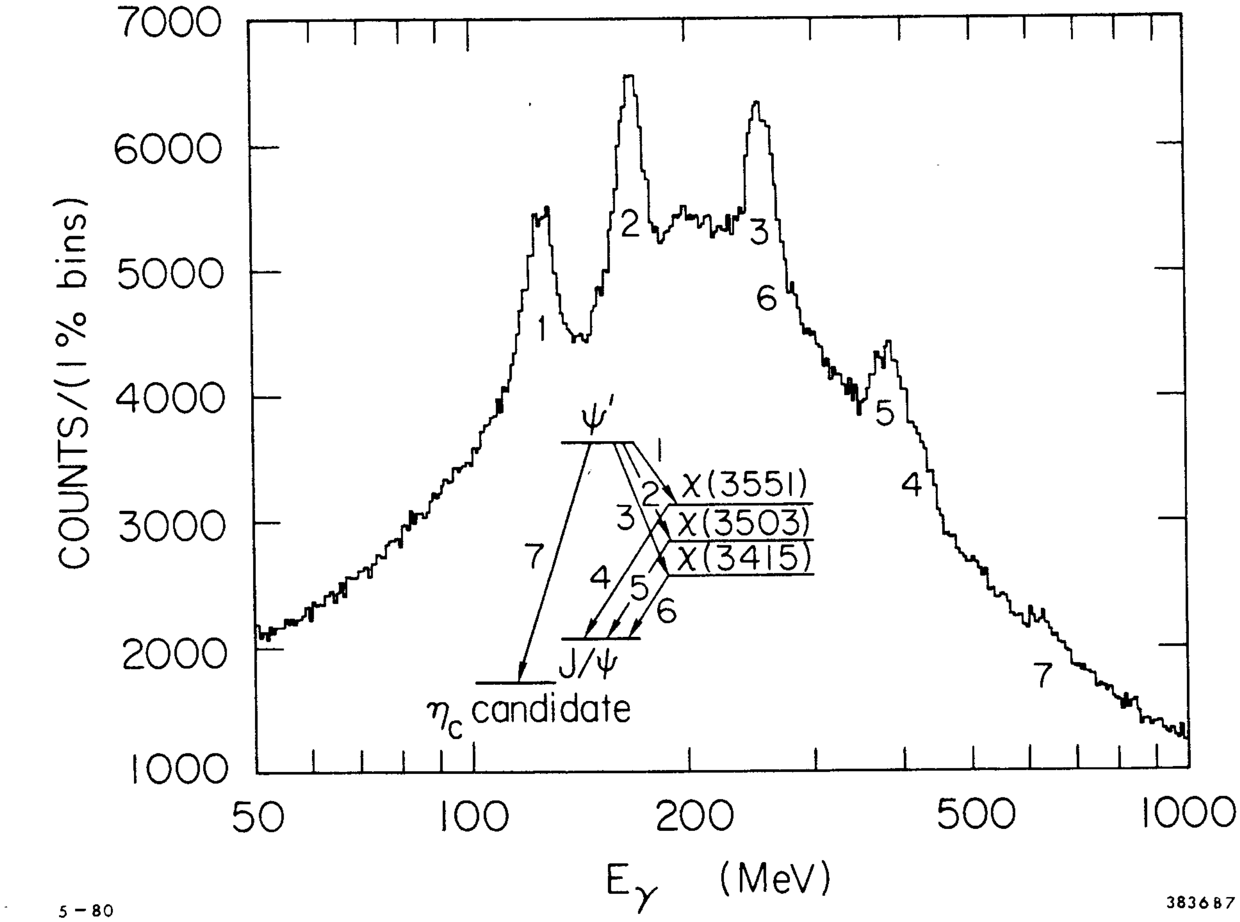

7000
6000
5000
4000
3000
2000
1000
COUNTS/(1% bins)
50
100
200
500
1000
E_γ (MeV)
1
2
3
4
5
6
7
ψ'
χ(3551)
χ(3503)
χ(3415)
J/ψ
η_c candidate
5-80
3836B7

Fig. 1

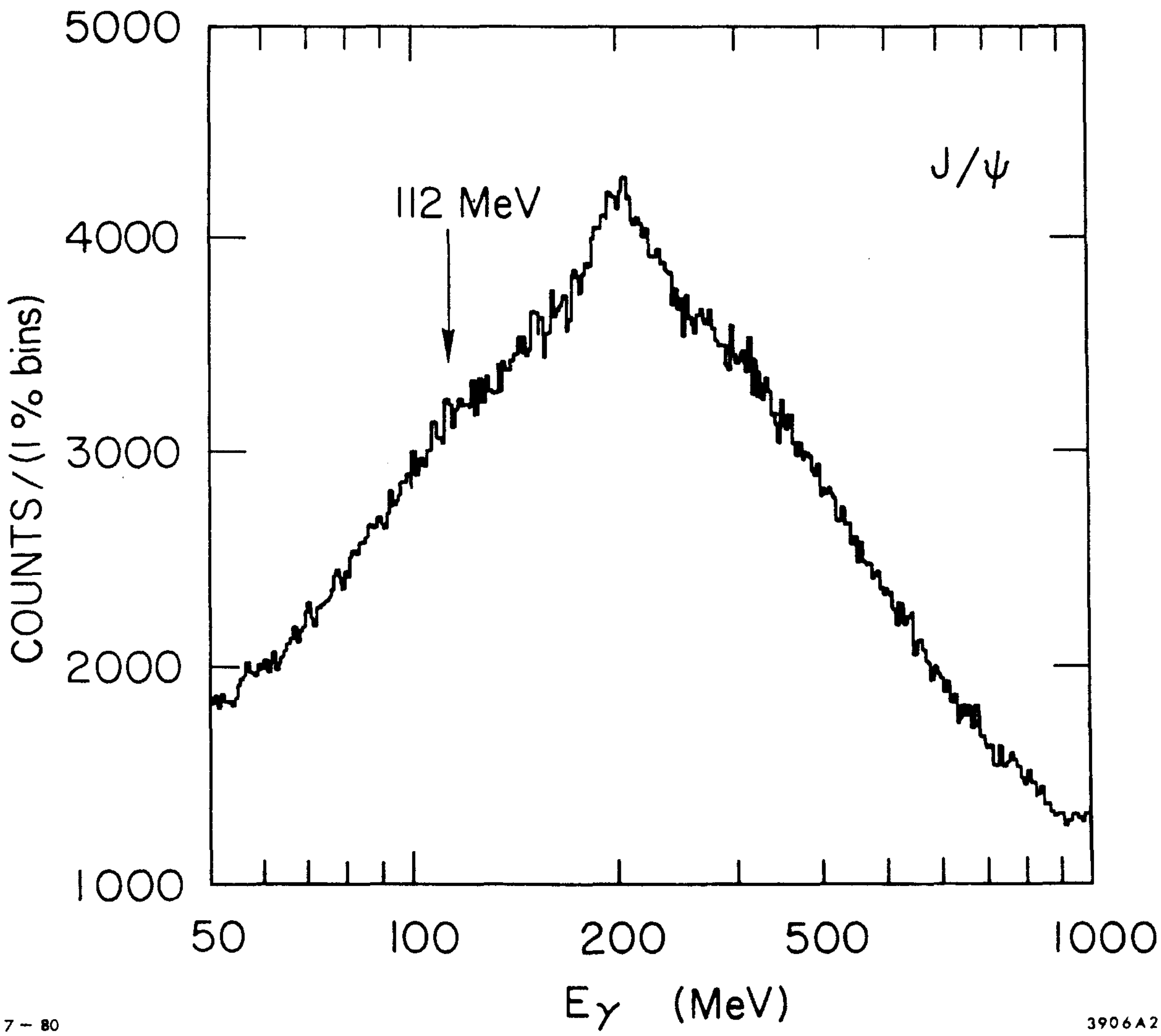
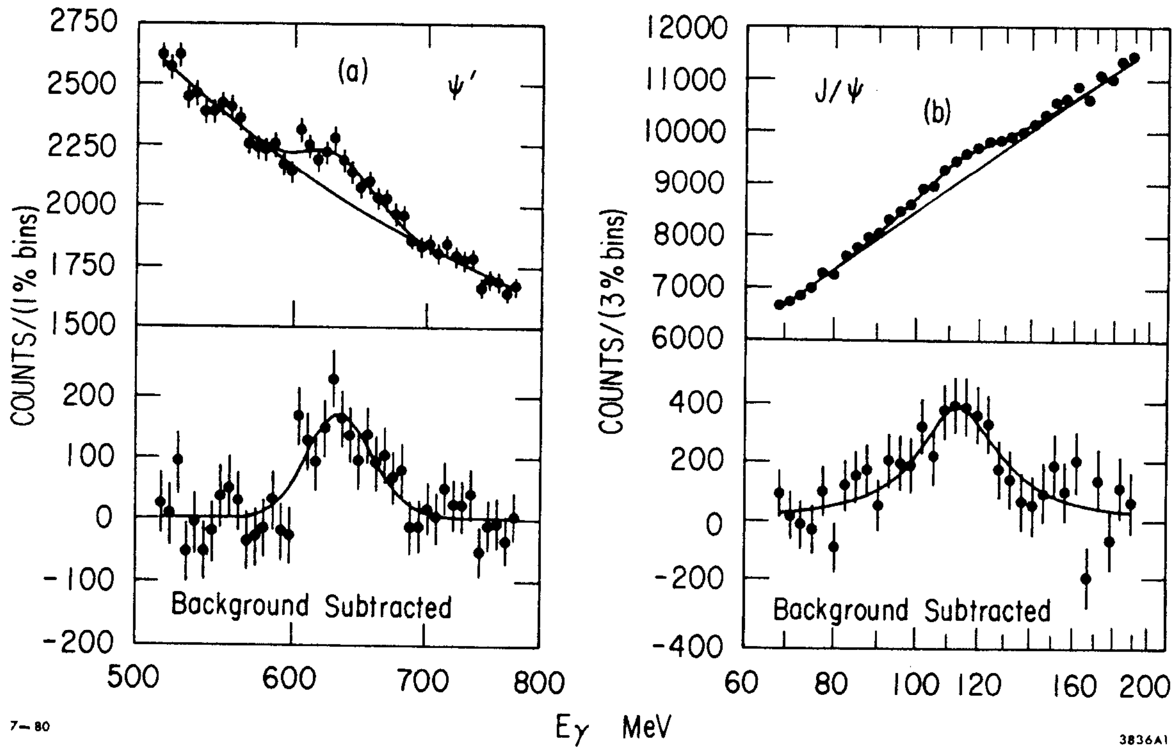

5000
4000
3000
2000
1000
COUNTS/(1% bins)
112 MeV
J/ψ
50
100
200
500
1000
Eγ (MeV)
7-80
3906A2

Fig. 2



(a)
ψ′
J/ψ
(b)
COUNTS/(1% bins)
COUNTS/(3% bins)
Background Subtracted
Background Subtracted
Eγ MeV
7–80
3836A1

Fig. 3

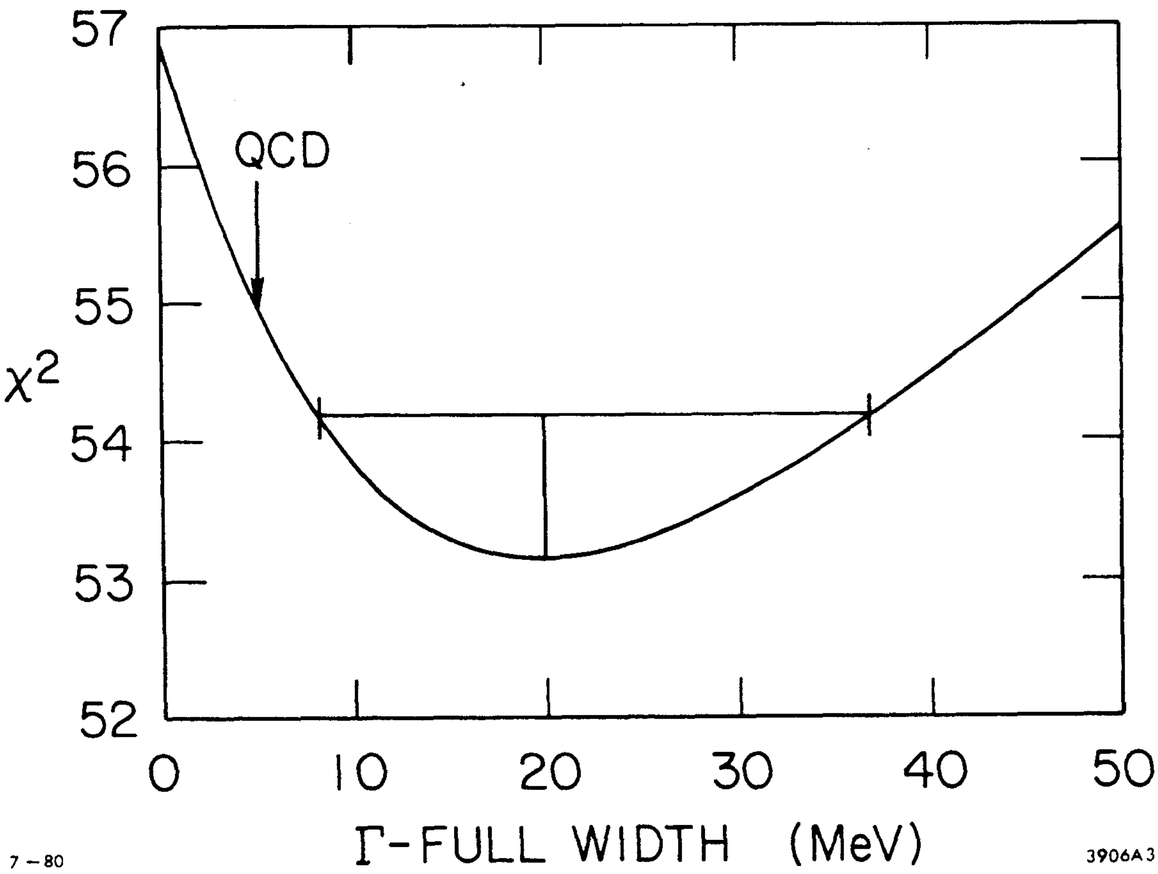

57
56
55
54
53
52
χ²
QCD
0
10
20
30
40
50
Γ-FULL WIDTH (MeV)
7 – 80
3906A3

Fig. 4

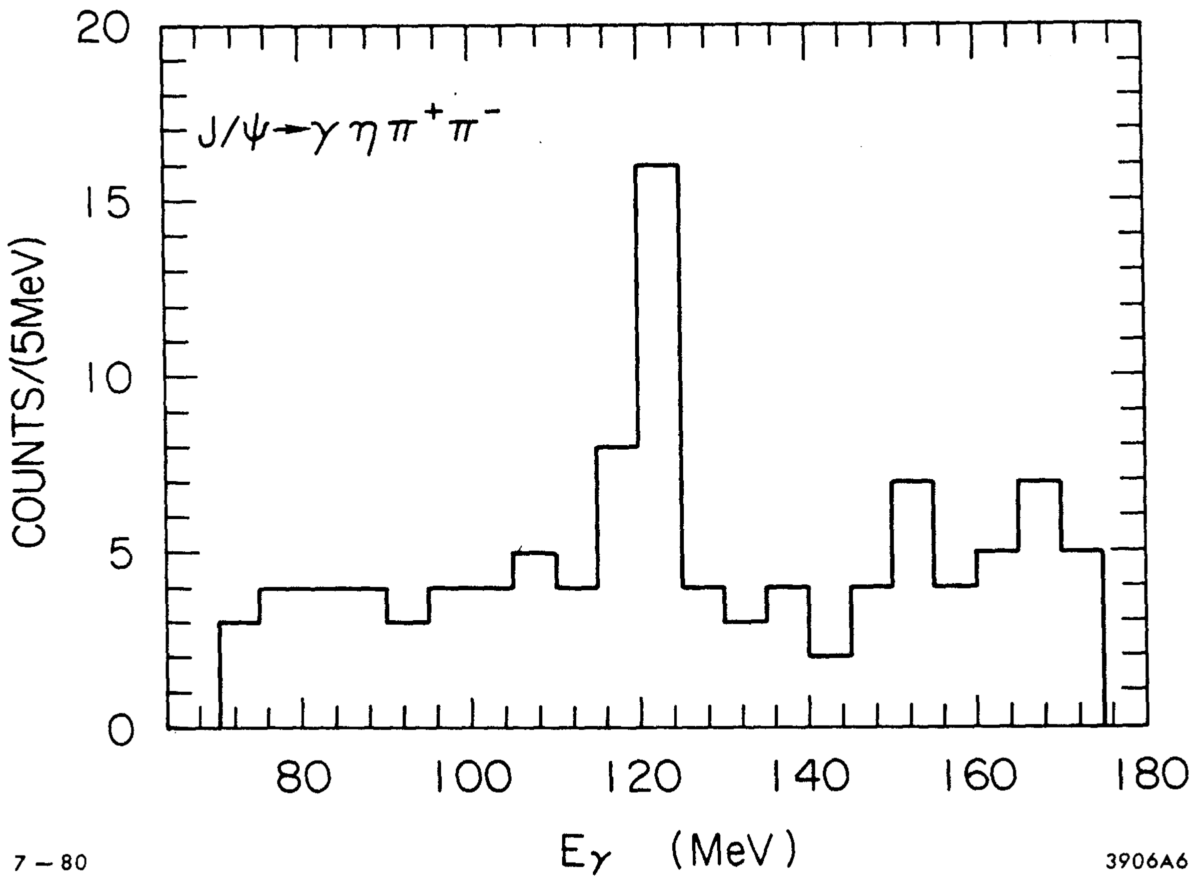

J/ψ→γ η π⁺π⁻
COUNTS/(5MeV)
0
5
10
15
20
80
100
120
140
160
180
Eγ (MeV)
7 – 80
3906A6

Fig. 5