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J/ψ Radiative decays into $\pi\pi\gamma$ and $KK\gamma$

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Abstract: The radiative decays of J/ψ into $f\gamma$, $f'\gamma$, $\pi\pi\gamma$ and $KK\gamma$ have been measured using the double arm spectrometer DASP at DORIS. We find $B(J/\psi \to f\gamma) = \frac{J/\psi \to f\gamma}{J/\psi \to \mathrm{all}} = (0.9 \pm 0.3)\cdot 10^{-3}$ to $(1.5 \pm 0.4)\cdot 10^{-3}$ depending on the multipole mode of the J/ψ decay, $B(J/\psi \to f'\gamma)/B(J/\psi \to f\gamma) \leq 1/3$ and that the relative strength of $\frac{J/\psi \to \pi\pi\gamma}{J/\psi \to \pi\pi\omega}$ at high $\pi\pi$ masses is smaller by an order of magnitude than its value at the f mass.

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The large rate of some J/ψ radiative decays[1,2] (e.g. $J/\psi \to \eta\gamma$, $\eta'\gamma$) and the small rate of others (e.g. $J/\psi \to \pi^o\gamma$) suggests[3] the possibility of a $c\bar{c}$ quark component in the η, η' mesons. The study of further J/ψ radiative decays will test these ideas and, if correct, can be used to determine the $c\bar{c}$ content of other "old" mesons. In this note we report on a measurement of J/ψ decays into $\pi\pi\gamma$ and $KK\gamma$ final states using the DASP detector at DORIS.

A detailed description of DASP has been given elsewhere[1,4]. It consists of two identical magnetic spectrometers positioned symmetrically with respect to the interaction point (outer detector, $\Delta\Omega \sim 0.9$ sr) and a nonmagnetic detector located between the magnets (inner detector, $\Delta\Omega \sim 9$ sr). The spectrometer arms provide high momentum resolution and good particle identification by time of flight, shower energy, and range measurement[4]. The inner detector can separate charged particles and photons and determine their direction with an accuracy of about one degree[1].

The total c.m. energy E was required to be in the interval $3.086 < E < 3.098$ GeV centered at the J/ψ mass. A total of $1.71\cdot 10^6$ J/ψ events were produced in this energy region. Candidates for $e^+e^- \to J/\psi \to f\gamma$ $(f \to \pi^+\pi^-)$ were sought among events with a photon plus two charged particles of which at least one had its momentum measured by the outer detector and was identified as a pion. A computer algorithm was used to preselect as $\pi\pi\gamma$ candidates events with at least one outer detector track and two or three additional inner detecotr tracks (charged or neutral). For these events all possible track permutations were fitted to the hypothesis $J/\psi \to \pi\pi\gamma$ (2C fit). Thus, for an event with one outer and 3 inner tracks all three possible inner track combinations were tried with both photon or pion mass assignments making six fits altogether. Only events for which at least one combination yielded a $\chi^2 < 20.0$ were retained. These were then scanned by physicists for the appropriate event topology to verify the track reconstruction and identification as provided by the computer programs. Out of 1116 scanned events, 350 were found to be consistent with the hypothesis $J/\psi \to \pi\pi\gamma$ ($\chi^2 < 20.0$). Most of the rejected events had more than three particles in the final state.

The Dalitz plot for the $\pi\pi\gamma$ events is shown in Fig. 1a. A strong concentration of events is seen near the boundaries which corresponds to low $\pi\pi$ or $\pi\gamma$ masses. The invariant $\pi\pi$ and $\pi\gamma$ mass distributions are plotted in Figs. 1b and 1c where enhancements are seen at the rho mass. A significant enhancement around 1250 MeV (f region) is also seen in the $\pi\pi$ mass distribution (Figs. 1a and 1b). Since $J/\psi \to \rho^o\gamma$ is forbidden by charge conjugation, we assume that the enhancements in the rho region are due to

$$J/\psi \to \pi^o \rho^o (\pi^o \to \gamma\gamma) \quad (1a)$$

or

$$J/\psi \to \pi^{\pm}\rho^{\mp} (\rho^{\mp} \to \pi^{\mp}\pi^o ,\ \pi^o \to \gamma\gamma) \quad (1b)$$

where one γ from π^o decay escaped detection. This interpretation is supported by the charged pion angular distribution for effective $\pi\pi$ and $\pi\gamma$ masses in the rho region. These distributions (not shown here) are roughly proportional to $\sin^2\Theta$ as expected for reactions (1a) and (1b). The χ^2 distributions for $J/\psi \to \pi\pi\gamma$ events in the $\rho^o(m^2_{\pi\pi} \le 1.0\ GeV^2)$ plus $\rho^{\pm}(m^2_{\pi\gamma} \le 1.0\ GeV^2)$ bands and in the $f(1.0 \le m^2_{\pi\pi} \le 2.0\ GeV^2)$ band are plotted in Fig.'s 2a,b. The distribution for events in the ρ-band is much wider than expected for a 2C fit, whereas events in the f-band are in agreement with the expected distribution for $J/\psi \to \pi\pi\gamma$. This shows that the 1250-MeV peak corresponds to genuine $\pi\pi\gamma$ events. The width and mass of the 1250-MeV peak are consistent with being the f. We therefore attribute the peak to

$$J/\psi \to f\gamma \to \pi^+\pi^-\gamma \quad (2)$$

Monte-Carlo calculations which simulated reactions (1a), (1b) and (2) were used to calculate the detection efficiency for the decay $J/\psi \to f\gamma$ and for the background below the f peak. Gaussian distributed errors, derived from the experimental data, were imposed on the Monte-Carlo events which were fitted to $J/\psi \to \pi\pi\gamma$ using the same routines as for the data. Masses and widths from the Particle Data Group (M_f = 1.271 GeV, Γ_f = 0.180 GeV, M_ρ = 0.773 GeV and Γ_ρ = 0.152 GeV) were used. For f production the form of the angular distribution $I(\Theta,\Phi,\chi,\psi)$, where Θ,Φ and χ,ψ refer to the f production and decay angles in the helicity frame respectively+), is not unique. We therefore tried $I(\Theta,\Phi,\chi,\psi)$ = const. and distributions expected for pure

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+) To be more specific, Θ is the angle between the f and the e^+ in the e^+e^- frame. χ and ψ are the polar and azimuthal angles of the π^+ in the f helicity frame, i.e. in the Cartesian system with unit vectors $\hat{X}, \hat{Y}, \hat{Z}$, where $\hat{Z}$ is opposite to the γ direction, $\hat{Y}$ parallel to $(e^+ \times \gamma)$ and $\hat{X} = (\hat{Y} \times \hat{Z})$ all in the f rest frame.

E1, M2 and E3 transition in $J/\psi \to f\gamma$ +). For ρ production (vector $\to$ vector + pseudoscalar) the angular distribution $I \propto \sin^2\chi(1 + \cos^2\Theta + \sin^2\Theta \cos 2\psi)$ was used. The numbers n_i of $f\gamma$, $\rho^o\pi^o$ and $\rho^{\pm}\pi^{\mp}$ events, detected as $\pi\pi\gamma$'s, (i = 1,2,3 respectively) were then calculated in the following way. First the Dalitz plot was divided into four regions: The f band ($1.0\ GeV^2 < m^2_{\pi\pi} < 2.0\ GeV^2$), the ρ^o band ($m^2_{\pi\pi} < 1.0\ GeV^2$), the $\rho^{\pm}$ band ($m^2_{\pi\gamma} < 1.0\ GeV^2$), and the rest of the Dalitz plot. Then the fractions α_{ik} of f, ρ^o and $\rho^{\pm}$ events to be observed as $\pi\pi\gamma$'s in each region (k = 1,2,3) were calculated. Finally, the n_i's were obtained by solving the equations $\sum \alpha_{ik} n_i = m_k$ (k = 1,2,3) where m_k is the number of observed $\pi\pi\gamma$ events in the k-th region. We find that more than 90 % of the observed events are due to reactions (1a), (1b) and (2).

The same fit yields (30.4 ± 6.6) $f\gamma$ events, detected as $\pi\pi\gamma$'s, in our experiment. Computing the Monte-Carlo efficiency for an isotropic f production and decay, and normalizing to the $J/\psi \to \mu^+\mu^-$ events observed in the same experiment, we find *) $B(J/\psi \to f\gamma) = (1.1 \pm 0.3)\ 10^{-3}$. For pure E1, M2 and E3 $J/\psi \to f\gamma$ transitions we obtain $B(J/\psi \to f\gamma) = (0.9 \pm 0.3)\ 10^{-3}$, $(1.5 \pm 0.4)\ 10^{-3}$ and $(1.0 \pm 0.3)\ 10^{-3}$ respectively. The errors in the branching ratio contain statistical and systematic uncertainties. This procedure was repeated with different χ^2 cuts and fiducial regions, on both the data and Monte-Carlo events, yielding the same results within errors.

As a consistency check, we determined from our data the $\rho^o\pi^o$ and $\rho^{\pm}\pi^{\mp}$ branching ratios which have been measured previously[5-7]. Repeating the above procedure yields $B(J/\psi \to \rho^o\pi^o) = (0.43 \pm 0.10)\ 10^{-2}$ and $B(J/\psi \to \rho^{\pm}\pi^{\mp}) = (0.93 \pm 0.18)\ 10^{-2}$. These values are in good agreement with $B(J/\psi \to \rho^{\pm}\pi^{\mp}) = (0.78 \pm 0.19)\ 10^{-2}$ as measured by DASP[5] using the outer detector only and with $B(J/\psi \to \rho\pi) = (1.3 \pm 0.3)\ 10^{-2}$ as given in ref. (6).

+) Explicit expressions for $I(\Theta,\Phi,\chi,\psi)$ are:

E1: $\frac{1}{160\pi}\ [3T_1 + 18T_2 + 18T_3 + 3T_4 + 6T_5 - 18T_6]$

M2: $\frac{1}{160\pi}\ [15T_1 + 10T_2 + 10T_3 + 5T_4 - 10T_5 + 10T_6]$

E3: $\frac{1}{160\pi}\ [12T_1 + 32T_2 + 2T_3 - 8T_4 + 4T_5 + 8T_6]$

where : $T_1 = (1 + \cos^2\Theta)\ |Y_2^0|^2$, $T_2 = \sin^2\Theta |Y_2^1|^2$, $T_3 = (1 + \cos^2\Theta)\ |Y_2^2|^2$

$T_4 = \sqrt{6}\ \sin 2\Theta \mathrm{Re}(Y_2^1 Y_2^{0*})$, $T_5 = \sqrt{6}\ \sin^2\Theta\ \mathrm{Re}(Y_2^2 Y_2^{0*})$, $T_6 = \sin 2\Theta\ \mathrm{Re}(Y_2^2 Y_2^{1*})$

and $Y_\ell^m = Y_\ell^m(\chi,\psi)$

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*) We have used $B(J/\psi \to \mu^+\mu^-) = 0.069 \pm 0.009$ as given by Boyarski et al., Phys. Rev. Lett. 34 (1975) 1357 and $B(f \to \pi^+\pi^-) = 0.54$.

Our values for $B(J/\psi \to f\gamma)$ are smaller but still consistent within errors with an earlier measurement of $(2.0 \pm 0.7)\ 10^{-3}$ by the PLUTO-Collaboration[8].

Comparing the radiative decay to the related strong decay $J/\psi \to f\omega$, we find $R_f = \frac{B(J/\psi \to f\gamma)}{B(J/\psi \to f\omega)} \cdot \frac{PS(f\omega)}{PS(f\gamma)} \approx 0.5$ where $(PS(f\omega)/PS(f\gamma)) = 0.89$ is a small correction due to the different phase space. The ratio R_f was evaluated for $B(J/\psi \to f\gamma) = 1.1\ 10^{-3}$ and using the value for $B(J/\psi \to f\omega)$ given in ref. (9). The same R_f value is obtained using $B(J/\psi \to f\gamma)$ and $B(J/\psi \to f\omega)$ from references (8) and (10). This value for R_f is of order 1, whereas vector dominance with ω predicts a value of the order of 10^{-3}. Also note that the branching ratio $B(J/\psi \to f\gamma)$ is similar to the values measured for $J/\psi \to \eta\gamma$ and $J/\psi \to \eta'\gamma$. This may indicate that the wave function of the f also contains a small $c\bar{c}$ component and that the radiative decay proceeds via this component as has been conjectured for the η and η' decays.

We have also determined the branching ratio for $J/\psi \to \pi^+\pi^-\gamma$ for $\pi^+\pi^-$ masses outside the f-region.

For $\pi\pi\gamma$ events with $m_{\pi\pi} < 1.0$ GeV (ε region) we find that all events are consistent with $\rho^o\pi^o$ decays as can be deduced from the amount of $\rho^\pm\pi^\mp$ events with the same χ^2 and $m_{\pi\pi}$ cuts. However, with the extreme pessimistic assumption that all events with $\chi^2 < 6.0$ in this mass region are genuine radiative decays an upper limit of $B(J/\psi \to \pi^+\pi^-\gamma) = (0.7 \pm 0.2)\ 10^{-3}$ is obtained for $m_{\pi\pi} < 1.0$ GeV.

The radiative decay into a $\pi\pi$-system with a mass above 1.6 GeV was determined by selecting events with $\chi^2 < 6.0$ and $m^2_{\pi\gamma} > 1.2\ \text{GeV}^2$. The resulting $\pi\pi$-mass distribution is plotted in Fig. 3a. A total of 12 events with $m_{\pi\pi} > 1.6$ GeV satisfied the cuts. By comparing the experimental χ^2 distribution for these events with the distributions predicted for $\pi^+\pi^-\gamma$ and $\pi^+\pi^-\pi^o$, we estimated a radiative signal of (6.1 ± 3.9) events. To evaluate the detection efficiencies including corrections resulting from the cuts on χ^2 and the $\pi\gamma$-mass, we assumed that the $\pi\pi$-system is produced and decays isotropically. This yields a branching ratio of $B(J/\psi \to \pi^+\pi^-\gamma) = (1.7 \pm 1.1)\ 10^{-4}$ for $m_{\pi\pi} > 1.6$ GeV. This can be compared to the decay $J/\psi \to \pi^+\pi^-\omega$. We find

$R(m_{\pi\pi} > 1.6\ \text{GeV}) = \frac{B(J/\psi \to \pi^+\pi^-\gamma)}{B(J/\psi \to \pi^+\pi^-\omega)} \cdot \frac{PS(\pi\pi\omega)}{PS(\pi\pi\gamma)} = (0.04 \pm 0.03)$ taking the value for $B(J/\psi \to \pi^+\pi^-\omega)$ from ref. (9). This value for R is smaller than the value for R_f by an order of magnitude. This might indicate that the high mass $\pi^+\pi^-$ state has a smaller $c\bar{c}$ component than the f.

A procedure similar to the one described above was used to select $K^+K^-\gamma$ events. Events with a photon plus two charged tracks of which at least one was identified as a kaon were fitted to the hypothesis $J/\psi \to K^+K^-\gamma$ (2C fit). The K^+K^- invariant mass distribution is shown in Fig. 3b for all events with $\chi^2 < 20.0$, and for events with $\chi^2 < 6.0$ and $m^2_{K\gamma} > 1.2\ \text{GeV}^2$ (shaded area). The $m^2_{K\gamma}$ cut was introduced to eliminate $K^\pm K^{\mp *}(890)$ reflections. We find 4 events ($\chi^2 < 6$) with a KK mass between 1.553 and 1.572 GeV which differ by 40 to 60 MeV from the f'(1516) mass compared to an experimental mass resolution at this mass value of ~25 MeV. The branching ratio $J/\psi \to f'\gamma$ was therefore evaluated for two extreme possibilities: 1) We have no candidates for $J/\psi \to f'\gamma$ ($f' \to K^+K^-$) which yields+) a 90 % confidence upper limit $B(J/\psi \to f'\gamma) = 1.9\ 10^{-4}$, 2) Assuming all 4 events are genuine $f'\gamma$ events we obtain+) $B(J/\psi \to f'\gamma) = (3.4 \pm 1.8)\ 10^{-4}$. This yields $B(J/\psi \to f'\gamma)/B(J/\psi \to f\gamma) \leq 0.3$. Pure singlet mixing with $c\bar{c}$ would give $\frac{B(J/\psi \to f'\gamma)}{B(J/\psi \to f\gamma)} = 0.5$ (11). However, note that the similar branching ratios found for $\eta\gamma$ and $\eta'\gamma$ indicate that the mixing does not respect the SU(3) assignment. For $m_{KK} > 1.6$ GeV we find 7 events with $\chi^2 < 6$ yielding $B(J/\psi \to K^+K^-\gamma) = (2.5 \pm 1.0)\ 10^{-4}$. This should be taken as an upper limit since the data have not been corrected for possible background.

Our results for the branching ratios are summarized in Table I.

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+) Isotropic production and decay of the f' and $B(f' \to K^+K^-) = 0.5$ were assumed.

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Table I: Radiative decay modes of the $J/\psi(3095)$ into $\pi\pi\gamma$ and $KK\gamma$.

Reaction	$\pi\pi$(KK) mass region	Angular distribution[a)]	Branching Ratio	
$J/\psi \to f\gamma$		Isotropy	1.1 ± 0.3	10^{-3}
		E1	0.9 ± 0.3	10^{-3}
		M2	1.5 ± 0.4	10^{-3}
		E3	1.0 ± 0.3	10^{-3}
$J/\psi \to f'\gamma$		Isotropy	≤ 0.34	10^{-3}
$J/\psi \to \pi^+\pi^-\gamma$	<1.0 GeV	Isotropy	≤ 0.7	10^{-3}
	>1.6 GeV	Isotropy	0.17 ± 0.11	10^{-3}
$J/\psi \to K^+K^-\gamma$	>1.6 GeV	Isotropy	≤ 0.25	10^{-3}

a) Isotropy denotes an isotropic distribution for both production and decay except for $J/\psi \to \pi\pi\gamma$ with $m_{\pi\pi} < 1.0$ GeV where a production distribution of $1 + \cos^2\Theta$ was used.

Figure Captions

1. (a) Dalitz plot for $e^+e^- \rightarrow J/\psi \rightarrow \pi^+\pi^-\gamma$ events with $\chi^2 < 20$.
   (b) $\pi^+\pi^-$ invariant mass distribution for $\pi^+\pi^-\gamma$ with $\chi^2 < 20$.
   The shaded area represents events with $\chi^2 < 6$. The line represents reflection from $\rho^\pm\pi^\mp$ events as calculated by Monte-Carlo ($\chi^2 < 6$).
   (c) $\pi^\pm\gamma$ invariant mass distribution for $\pi^+\pi^-\gamma$ events with $\chi^2 < 20$. Only the low mass $\pi\gamma$ combination is shown.

2. χ^2 distributions for $\pi^+\pi^-\gamma$ events (a) in the ρ^0 band ($m^2_{\pi\pi} < 1.0$ GeV^2) or in the $\rho^\pm$ band ($m^2_{\pi\gamma} < 1.0$ GeV^2) (b) in the f band (1.0 GeV^2 < $m^2_{\pi\pi}$ < 2.0 GeV^2). The lines represent the expected distributions in these bands as calculated by Monte-Carlo.

3. (a) $\pi^+\pi^-$ invariant mass distribution for $\pi^+\pi^-\gamma$ events with $\chi^2 < 6$ and $m^2_{\pi\gamma} > 1.2$ GeV^2 for both $\pi\gamma$ combinations.
   (b) K^+K^- invariant mass distribution for $K^+K^-\gamma$ events with $\chi^2 < 20$. The shaded area represents $K^+K^-\gamma$ events with $\chi^2 < 6$ and $m^2_{K\gamma} > 1.2$ GeV^2 for both $K\gamma$ combinations.

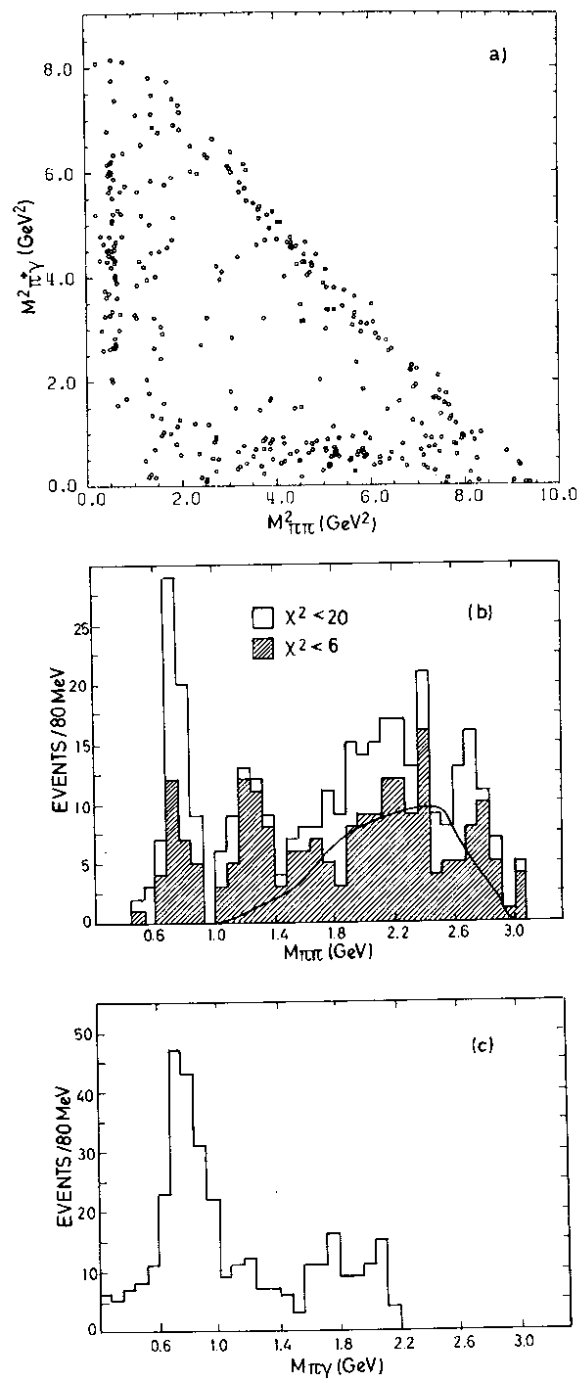
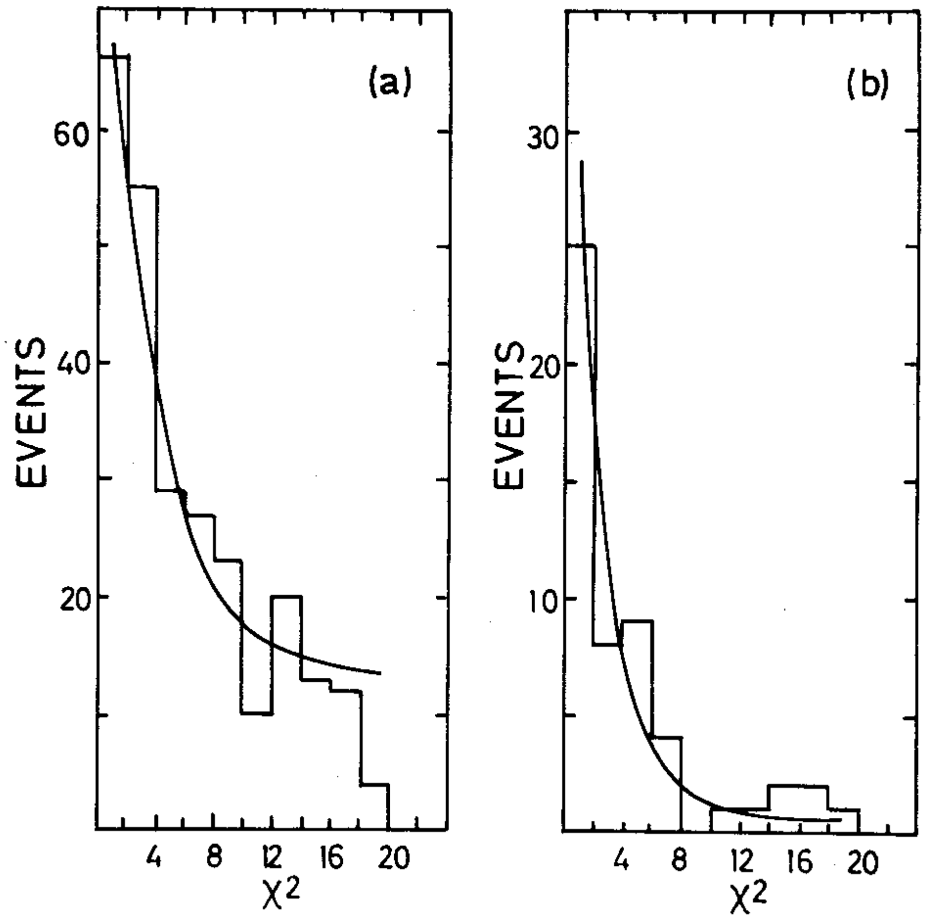
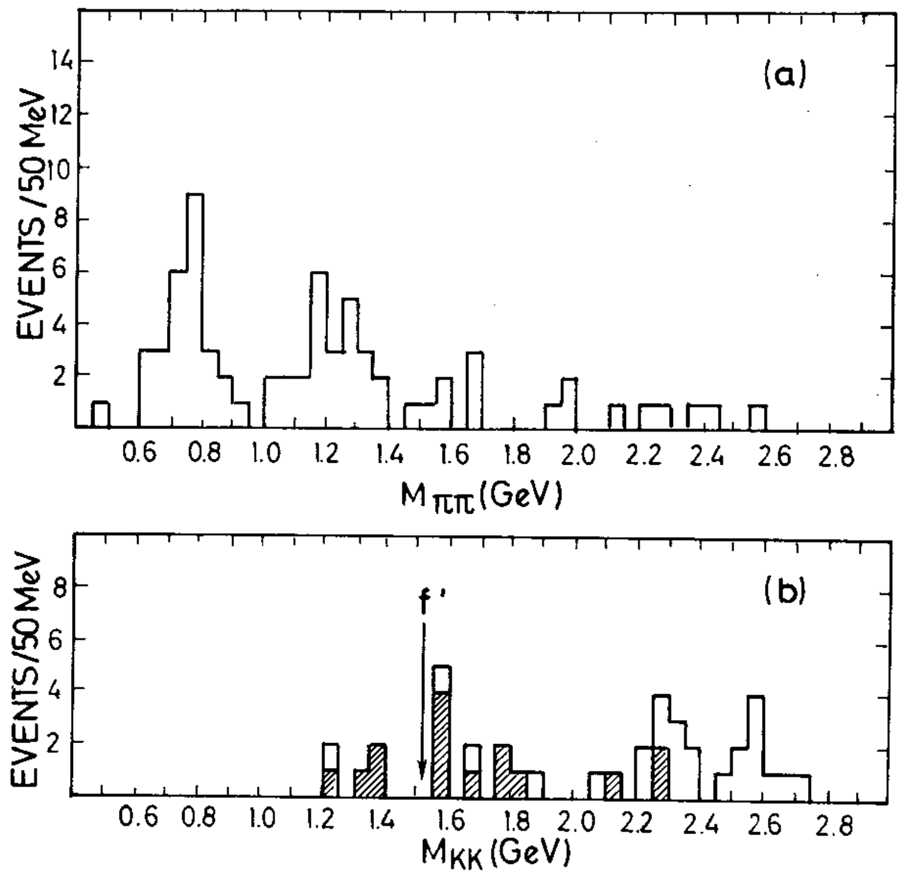


Fig.1



(a)
(b)
EVENTS
60
40
20
30
10
4
8
12
16
20
χ^2

Fig.2



(a)
EVENTS/50 MeV
14
12
10
8
6
4
2
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
$M_{\pi\pi}$ (GeV)
(b)
f'
M_{KK} (GeV)

Fig.3