Radiative decay of the ψ' into $\gamma\pi^+\pi^-$,γK^+K^- and $\gamma K^0_S K^0_S$

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Abstract

The 3.6×10^6 ψ'data collected by the BES detector has been used to study the ψ' radiative decay into $\gamma\pi^+\pi^-$,γK$^+$K$^-$ and γK^0_SK^0_S at the region where the $\pi^+\pi^-$,K$^+$K$^-$ and K^0_SK^0_S invariant masses are smaller than 3 GeV. The f$_2$(1270) and f$_J$(1710) signals have been seen and the branch fraction of $\psi' \to \gamma f_2(1270)$ and $\psi' \to \gamma f_J(1710) \to \gamma K\bar{K}$ have been measured. The results shows that these radiative decay modes are not suppressed from the "15% rule".

It is believed that the dominant processes of J/ψ and ψ' hadronic decay are through three gluons and the strong coupling constant a_s doesn't change significantly from the J/ψ mass to the ψ' mass. The lowest order perturbative QCD predicts the "15% rule" based on this assumption:

$$Q = \frac{B(\psi' \to X)}{B(J/\psi \to X)} = \frac{B(\psi' \to ggg)}{B(J/\psi \to ggg)} = \frac{B(\psi' \to l^+l^-)}{B(J/\psi \to l^+l^-)} = (14.6 \pm 2.2)\%$$

where X is an arbitrary non-charmonium state. Results from the Mark II experiment and the BES experiment show that most of the ψ'decay channels follow the theoretical prediction. But the ψ'decay into vector-pseudoscalar modes such as $\psi' \to \rho\pi$ and K^*K, as well as ψ'decay into vector-tensor modes are suppressed from the "15% rule".

The ψ' radiative decay modes are similiar to its hadronic decay modes with one of the gluon being replaced by a photon. And it is believed that the "15% rule" should also hold for radiative decay modes[1]. In this studying, we use the 93/94/95 ψ' data sets collected by BES to study the $\psi' \to \gamma\pi^+\pi^-$,$\gamma K^+K^-$ and $\gamma K^0_S K^0_S$ with $\pi^+\pi^-$,K^+K^- and $K^0_S K^0_S$ invariant mass below 3 GeV.

1 $\psi' \to \gamma\pi^+\pi^-$

The event selection for this channel starts from DST data with 2 charged tracks. The following criteia are imposed to each event:

1. Two charged tracks with $\sum Q_i = 0$ and the "mfit" parameter are 2 for both tracks.
2. At least one photon hit at Barrel Shower Counter and the energy deposited in it should be larger than 10 MeV.
3. The opening angle of these two charged tracks is smaller than 175^o. $\mid Z_1 - Z_2 \mid < 5cm$. A vertex can be found from these two charged tracks and the Z coordinate of the vertex satisfy $\mid Z_V \mid < 6cm$.

4. For each charged track, we asked $|\cos(\theta)| < 0.85$; $R_{xy} < 10cm$ and $Z < 15cm$; In order to remove $e^+e^- \to (\gamma)e^+e^-$ process, we required that for each track with momentum larger than 700 MeV, $E/P < 0.75$ and for both tracks, $(E_+/P_+ - 1)^2 + (E_-/P_- - 1)^2 > 0.4$. Also, to remove $\mu^+\mu^-$ events, we require that there should not be more than 3 layers being hit in Muon detector.

5. We did 4-C fits over $\pi^+\pi^-$ and all possible good photons and the photon in the $\gamma\pi^+\pi^-$ combination that has smallest χ^2 is selected as the radiative photon candidate and we required that probability of this χ^2 is larger than 0.01. Kinematic fit for $\gamma K^+K^-$is also done and should have a smaller χ^2 probability in order for this event to survive.

6. Finally, the opening angle between the radiative γ and any charged tracks should be larger than 15^o.

The $\pi^+\pi^-$invariant mass is shown in Fig. 1(a). While the $f_2(1270)$ signal is very obvious, there are also strong QED background presented. The initial state radiation process $e^+e^- \to \gamma\rho^0 \to \gamma\pi^+\pi^-$ contributes to the ρ^0 signal in the plot and $e^+e^- \to (\gamma)\mu^+\mu^-$ process contributes to the continuous background.

In order to remove these QED background, we fed the τ scan data collected by the BES detector into our program. The result is shown in Fig 1(b). We can scale these two histograms and subtract they to remove the QED background in ψ' data. However, the situation of the BES calorimeter at the time the τ scan data was taken was poor and this prevent us from scaling the two histograms by using the known integrated luminosities of the total ψ' data and τ data. Instead, we used the number of events with $\pi^+\pi^-$ invariant mass lower than 850 MeV on the two plots to scale them and then did the subtraction. The scaling factor is ~ 1.9. The result is shown in Fig. 2(a).

In order to fit the histogram in Fig. 2(a), we adopted a special form of relativistic Breit-Wigner function to descript the rather broad signal in ψ' radiative decay into two identical pseudo-scalars[2]:

$$\frac{d\sigma}{dm^2} = C|T|^2 \frac{P}{m_{\psi'}} \frac{Q}{m} \tag{1}$$

where:

- C is a constant that will be computed numerically based on normalization.
- m is the invariant mass of the two pseudo-scalars.
- P is the momentum of the $\pi^+\pi^-$ in ψ' rest frame.
- Q is the momentum of the $\pi^{+/-}$in $\pi^+\pi^-$'s rest frame.
- T is the invariant amplitude describing the production and decay of the $f_2(1270)$.

If we think that T has the form:

$$T = \frac{Q^s}{m_0^2 - m^2 - im_0\Gamma_{total}(E)}$$

where s is the spin of the resonant which is 2 for $f_2(1270)(J^{PC} = 2^{++})$. Consider that $f_2(1270) \to \pi\pi$ and $K\bar{K}$ made 90% of its total decay width, we can make a good approximation on the energy dependent width $\Gamma_{total}(E)$:

$$\Gamma_{total}(E) = \Gamma_0 \frac{m_0}{m} \times \frac{B(f_2 \to \pi\pi)\left[\frac{Q_\pi(m)}{Q_\pi(m_0)}\right]^{(2s+1)} + \theta(m_K) B(f_2 \to K\bar{K})\left[\frac{Q_K(m)}{Q_K(m_0)}\right]^{(2s+1)}}{B(f_2 \to \pi\pi) + B(f_2 \to K\bar{K})} \tag{2}$$

$$\theta(m_K) = \theta(m - (m_K + m_{\bar{K}})) = \begin{array}{l} 0 \text{ if } m < (m_K + m_{\bar{K}}); \\ 1 \text{ if } m > (m_K + m_{\bar{K}}); \end{array}$$

where θ is step function, m_0 and Γ_0 are the mass and width of $f_2(1270)$ on PDG.

The background is described by modified Legendre polynomial functions:

$$\frac{1}{m_{\max} - m_{\min}} \sum_{i=0}^{N_{poly}} b_i p_i(x) P(m) Q(m) \tag{3}$$

$$x = 2\frac{m - m_{\min}}{m_{\max} - m_{\min}} - 1;\; x \in [-1, 1]$$

where $p_i(x)$'s are the Legendre polymornial. b_i's are coefficients and $b_0 = 1$ for normalization if P and Q are not presented at here. The reason P and Q are here is to keep the Lorentz invariant phase space behavior. The background function's normalization is done numerically.

With the mass and width of $f_2(1270)$ fixed at PDG values, we fit the histogram with a D-wave Breit-Wigner function and it gives us 216.3 ± 17.8 events. The efficiency of this analysis is 38.6% calculated from the uniform phase space Monte Carlo simulation with D-wave Breit-Wigner included, as shown in Fig. 2(b). Assuming $B(f_2(1270) \to \pi^+\pi^-) : B(f_2(1270) \to \pi^0\pi^0) = 2 : 1$ according to the isospin, we obtain:

$$B(\psi' \to \gamma f_2(1270)) = (2.71 \pm 0.22 \pm 0.45) \times 10^{-4}$$

where the first error is statistical and the second error is systematic. Table 1 lists the number of events survived various cuts for both ψ' data and Monte Carlo data. Table 2 lists the major sources of systematic error. In Fig.2(a) there is also a potential signal of $f_J(1700) \to \pi^+\pi^-$ but we didn't try to fit the mass plot with it.

Comparing our result of $B(\psi' \to \gamma f_2(1270))$ with $B(J/\psi \to \gamma f_2(1270)) = (13.8 \pm 1.4) \times 10^{-4}$ on PDG, we get the ratio of these two branching fractions:

$$Q = \frac{B(\psi' \to \gamma f_2(1270))}{B(J/\psi \to \gamma f_2(1270))} = (19.6 \pm 1.6 \pm 3.3)\%$$

The PDG value of $B(J/\psi \to \gamma f_2(1270))$ is actually obtained from a slightly improperly handled analysis. If we use the Mark III's result of $B(J/\psi \to \gamma f_2(1270)) = (15.6 \pm 1.4) \times 10^{-4}$[3], we then have:

$$Q = \frac{B(\psi' \to \gamma f_2(1270))}{B(J/\psi \to \gamma f_2(1270))} = (17.3 \pm 1.4 \pm 2.9)\%$$

The $B(\psi' \to \gamma f_2(1270))$ we measured clearly shows that "*The 15% rule hold for ψ' radiative decay into $\gamma f_2(1270)$*".

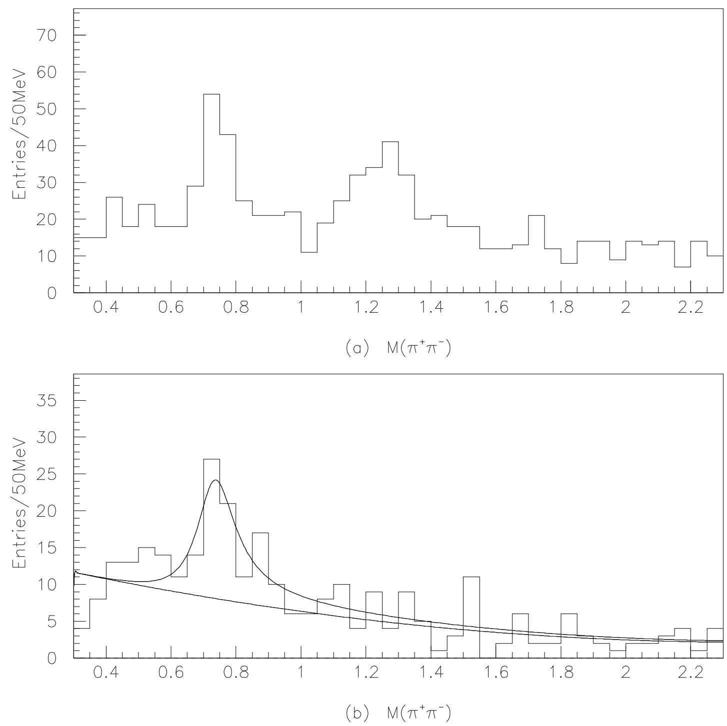


Figure 1: Invariant mass of $\pi^+\pi^-$in: (a) ψ'data; (b)τ scan data

	Data	Monte Carlo
Number of events come in	4786432	28610
$\sum Q_i = 0$; $N_\gamma > 0$; mfit=2	1062523	21082
γ hit at BSC, $E_\gamma > 10MeV$	992238	19334
$\lvert Z_1 - Z_2\rvert < 5cm$; $\lvert Z_V\rvert < 6cm$; $\theta_{\pi^+\pi^-} < 175^o$	344945	15778
Total μ layers< 3; $\lvert\cos(\theta_\pi)\rvert < 0.85$; $R_{xy} < 10cm$; $Z < 15cm$; $E/P < 0.75$; $(E_+/P_+ - 1)^2 + (E_-/P_- - 1)^2 > 0.4$	198173	14284
4C fit $\chi^2(\gamma\pi^+\pi^-) < 50$	5437	13292
$P_{\chi^2}(\gamma\pi^+\pi^-) > P_{\chi^2}(\gamma K^+K^-)$; $P_{\chi^2}(\gamma\pi^+\pi^-) > 0.01$; and remove QED background	N/A	11092
$\theta_{\gamma\pi} > 15^o$	286.8	11048

Table 1: Number of $\gamma\pi^+\pi^-$ events survive various cuts

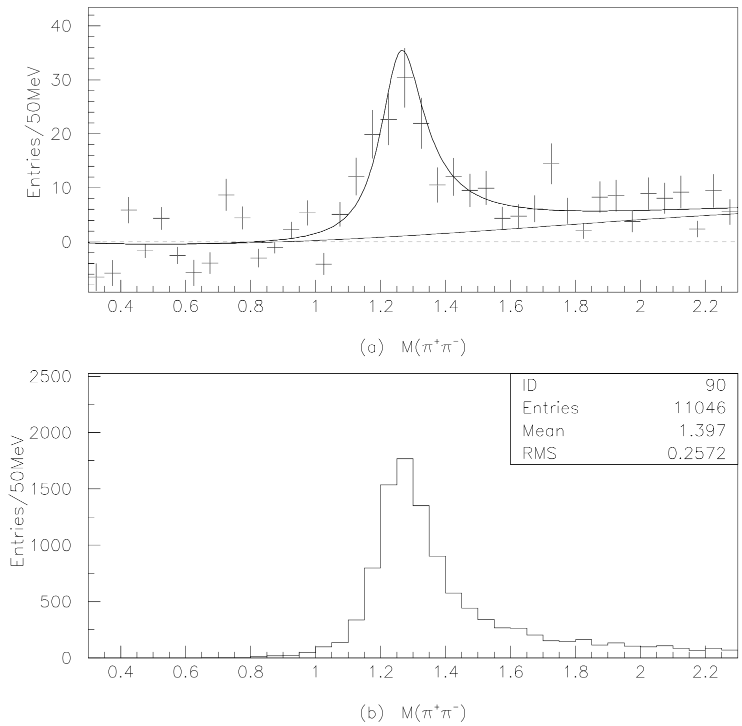


Figure 2: Invariant mass of $\pi^+\pi^-$ in (a) ψ' data, after QED background subtraction. (b) Monte Carlo data

Major cuts	$B(\psi' \to \gamma f_2(1270))$ difference(%)
$P_{\chi^2}(\gamma\pi^+\pi^-) > 0.01 \to 0.05$	13.7%
$\|Z_V\| < 6cm \to 5cm$	9.2%
$\theta_{\gamma\pi} > 15^o \to 10^o$	1.5%
Total	16.6%

Table 2: System Error estimation of $B(\psi' \to \gamma f_2(1270))$

2 $\psi' \to \gamma K^+K^-$

The event selection of this mode is similiar to that we used in $\gamma\pi^+\pi^-$ mode, except that we use the TOF and dE/dx information for particle identification:

- Charged track with momentum smaller than 700 MeV and have good Barrel Time-Of-Flight hits is considerred as a Kaon candidate if the TOF weight of Kaon is larger than 0.011(correspond to 3σ) and also larger than the TOF weight of pion.
- Charged track with momentum smaller than 600 MeV and with dE/dx information exist is considerred as a Kaon candidate if $\sigma_k < 3$ and $\sigma_k < \sigma_\pi$.
- If a low momentum track is not considerred as Kaon candidate by either TOF or dE/dx, the event is removed from further studying.
- 4-C Kinematic fits are also done on all combitions for both γK^+K^- and $\gamma\pi^+\pi^-$ hypothesises and and we required that $P_{\chi^2}(\gamma K^+K^-) > P_{\chi^2}(\gamma\pi^+\pi^-)$ and $P_{\chi^2}(\gamma K^+K^-) > 0.01$.

Fig. 3(a) and (b) show the invariant mass disbribution of K^+K^- in ψ' data and in τ scan data respectively. The initial state radiation process $e^+e^- \to \gamma\phi \to \gamma K^+K^-$ is clearly shown in the two plots. Note that the ratio of the number of ϕ events in these two plots is consistant with the ratio we got from $\gamma\pi^+\pi^-$ analysis. Fig. 4(a) shows the mass plot of K^+K^- in ψ' data after the removal of QED background. Fig. 4(b) is the signal from a modified phase space Monte Carlo which tells us the efficiency of 38.1%.

We fit $f_J(1710)$ signal in Fig. 4(a) by using a similiar relativistic Breit-Wigner that we used in the $\gamma\pi^+\pi^-$ studying. The J^{PC} of $f_J(1710)$ is $even^{++}$ on PDG. We assume the spin of the $f_J(1710)$ is zero but the fit is actually insensitive to the spin we assume. By fixing the mass and width of $f_J(1710)$ to the PDG value, the fit gives us (71.2 ± 10.6) events and a branching fraction of:

$$B(\psi' \to \gamma f_J(1710) \to \gamma K\bar{K}) = (1.04 \pm 0.15 \pm 0.18) \times 10^{-4}$$

The number of events survive each cut are listed in Table 3 and the systematic error sources are listed in Table 4. Compare to the PDG value of $B(J/\psi \to \gamma f_J(1710) \to \gamma K\bar{K}) = (9.7\pm1.2)\times10^{-3}$, we have the ratio of the two branching fractions:

$$Q = \frac{B(\psi' \to \gamma f_J(1710) \to \gamma K\bar{K})}{B(J/\psi \to \gamma f_J(1710) \to \gamma K\bar{K})} = (10.7 \pm 2.0 \pm 2.3)\%$$

Again, this result shows that "*The 15% rule hold for ψ' radiative decay into* $\gamma f_J(1710)$".

In additon, bump at $\sim 1.3GeV$ region on Fig. 4(a) might indicate $\psi' \to \gamma f_2(1270) \to \gamma K^+K^-$ signal. But we don't have a good fit over it. Bump at $\sim 1.5GeV$ region indicates there are events either from $\psi' \to \gamma f_2'(1525) \to \gamma K^+K^-$ or from the contermination of $\psi' \to \gamma f_2(1270) \to \gamma\pi^+\pi^-$ with both $\pi^+\pi^-$ been misidentified at K^+K^-. To estimate the contermination of this misidentification, we fed the $\psi' \to \gamma f_2(1270) \to \gamma\pi^+\pi^-$ Monte Carlo data to our γK^+K^- analysis program. The result is shown in Fig. 5(a). The contermination is estimated to be 1.5%, or 14.8 events in this mass region according to the branching fraction of $\psi' \to \gamma f_2(1270)$ we just obtained. They are peaked at $\sim 1.5GeV$ region. At this stage, it is hard to say what is really at $\sim 1.5GeV$ region. The invariant mass of K^+K^- from a Monte Carlo simulated $\psi' \to \gamma\pi^+\pi^-$ process is also shown in Fig. 5(b).

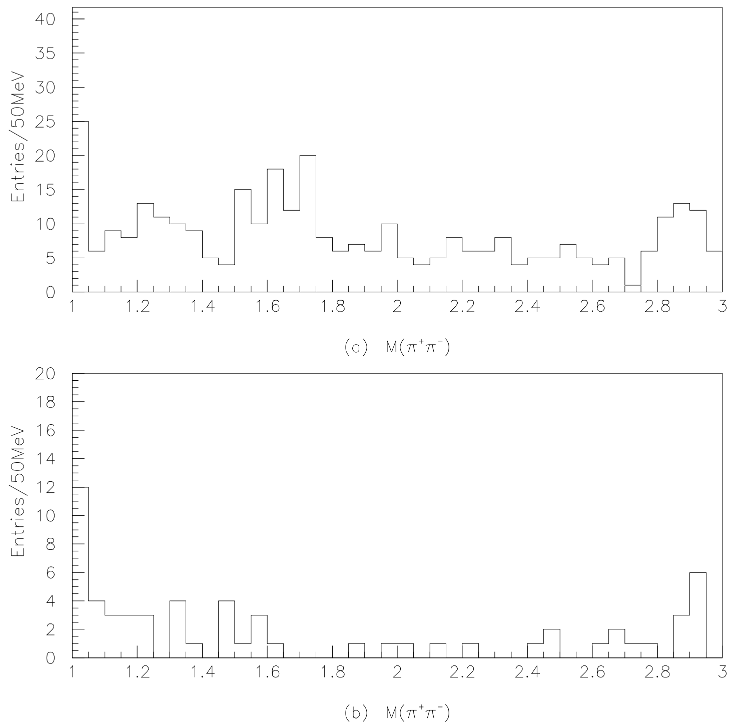


Figure 3: Invariant mass of K^+K^- in (a) ψ' data (b) τ scan data

	Data	Monte Carlo
Number of events come in	4786432	2861
$\sum Q_i = 0$; $N_\gamma > 0$; mfit=2	1062523	2060
γ hit at BSC, $E_\gamma > 10MeV$	992238	1877
$\|Z_1 - Z_2\| < 5cm$; $\|Z_V\| < 6cm$; $\theta_{\pi^+\pi^-} < 175^o$	344945	1529
Total μ layers< 3; $\|\cos(\theta_K)\| < 0.85$; $R_{xy} < 10cm$; $Z < 15cm$; $E/P < 0.75$; $(E_+/P_+ - 1)^2 + (E_-/P_- - 1)^2 > 0.4$; TOF and dE/dx cuts	65800	1368
4C fit $\chi^2(\gamma K^+K^-) < 50$	4336	1270
$P_{\chi^2}(\gamma K^+K^-) > P_{\chi^2}(\gamma\pi^+\pi^-)$; $P_{\chi^2}(\gamma K^+K^-) > 0.01$; and remove QED background	N/A	1071
$\theta_{\gamma\pi} > 15^o$	228.2	1070

Table 3: Number of γK^+K^- events survive various cuts

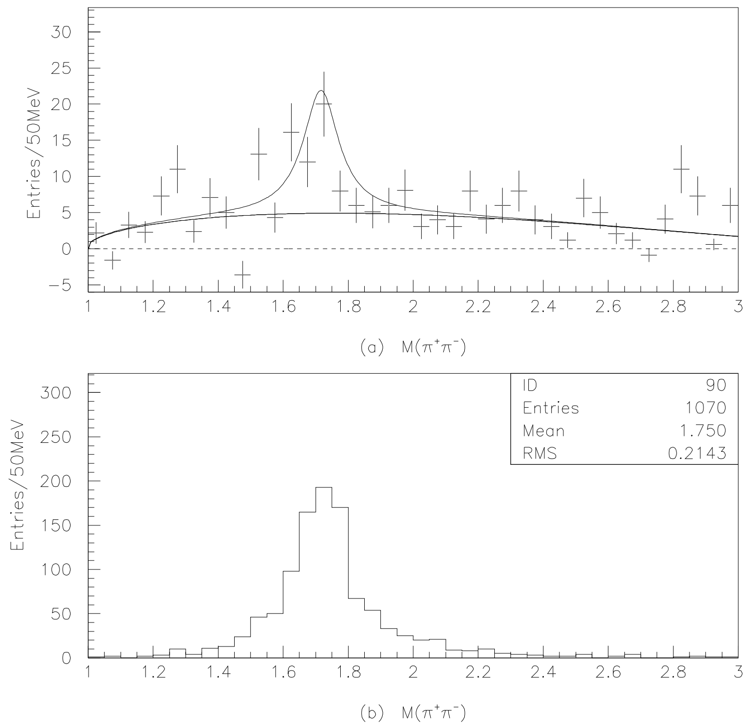


Figure 4: Invariant mass of K^+K^- in (a) ψ' data after the removal of QED background (b) Monte Carlo data.

Major cuts	$B(\psi' \rightarrow \gamma f_J(1710))$ difference(%)
$P_{\chi^2}(\gamma K^+K^-) > 0.01 \rightarrow 0.05$	16.3%
$\|Z_V\| < 6cm \rightarrow 5cm$	3.8%
$\theta_{\gamma\pi} > 15^o \rightarrow 10^o$	4.8%
Total	17.4%

Table 4: Systematic error estimation of $B(\psi' \rightarrow \gamma f_J(1710))$

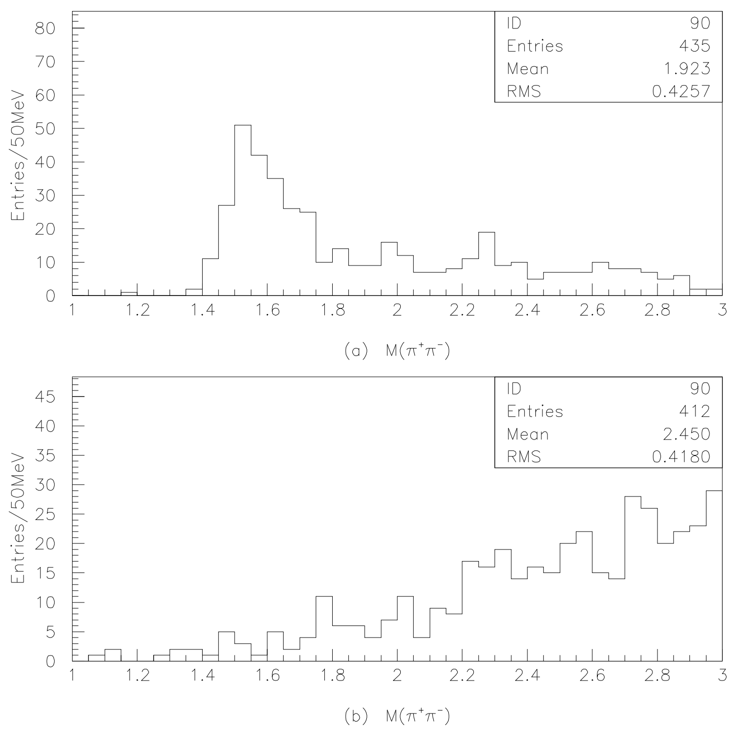


Figure 5: Invariant mass of K^+K^- in (a) $\psi' \to \gamma f_2(1270) \to \gamma\pi^+\pi^-$ Monte Carlo (b) $\psi' \to \gamma\pi^+\pi^-$ Monte Carlo

	Data	Monte Carlo
Number of events come in	2370479	14305
$\sum Q_i = 0$; $N_\gamma > 0$; mfit=2	569865	6479
γ hit at BSC, $E_\gamma > 10MeV$	563744	6004
$\|\cos(\theta_\pi)\| < 0.85$; $R_{xy} < 10cm$; $Z < 15cm$; $E/P < 0.75$	404649	4527
$P_{\chi^2}(\gamma\pi^+\pi^-\pi^+\pi^-) > 0.01$	12315	3393
$\|m_{\pi^+\pi^-} - m_{K_S^0}\| < 20MeV$	119	3035

Table 5: Numer of $\gamma\pi^+\pi^-\pi^+\pi^-$ events survive various cuts

Major cuts	$B(\psi' \to \gamma f_J(1710))$ difference(%)
$P_{\chi^2}(\gamma\pi^+\pi^-\pi^+\pi^-) > 0.01 \to 0.05$	22.4%
$\|m_{\pi^+\pi^-} - m_{K_S^0}\| < 20MeV \to 10MeV$	44.3%
Total	49.6%

Table 6: Systematic error estimation for $B(\psi' \to \gamma K_s^0 K_s^0)$

3 $\psi' \to \gamma K_S^0 K_S^0$

The events selection for this channel started from DST data with four charged tracks and is similiar to that we have done previously:

1. Four charged tracks with $\sum Q_i = 0$ and the "mfit" parameters are all 2.
2. At least one photon hit at Barrel Shower Counter and the energy deposite in it should be larger than 10 MeV.
3. For each charged track, we asked $|\cos(\theta)| < 0.85$; $R_{xy} < 10cm$; $Z < 15cm$; In order to remove electrons and positions, we required that $E/P < 0.75$ and for any tracks with momentum larger than 1.0GeV.
4. 4-C fits with all good photons as radiative photon candidate in all $\gamma\pi_1^+\pi_2^-\pi_3^+\pi_4^-$ combinations are done and we then select the combination with smallest $\sqrt{(m_{\pi_1^+\pi_2^-} - m_{K_S^0})^2 + (m_{\pi_3^+\pi_4^-} - m_{K_S^0})^2}$. We required that probability of this χ^2 is larger than 0.01.
5. Various plots are shown in Fig. 6. Fitting Fig. 6(b) with a gauss function gives us the mass resolution of $m_{K_S^0}$ equals $8.9MeV$. So we apply another cut: for each pair of $\pi^+\pi^-$, we required $|m_{\pi^+\pi^-} - m_{K_S^0}| < 20MeV$.

Fig 8 show the invarianat mass of $\pi^+\pi^-\pi^+\pi^-$. The phase space Monte Carlo (Fig 8(b)) tells us the efficiency of the program is 21.2%. Since there aren't many events in Fig 8(a), we simply count the number of events $\sim 1.7GeV$ which gives us $(6 \pm \sqrt{6})$ events and branching fraction:

$$B(\psi' \to \gamma f_J(1710) \to \gamma K\bar{K}) = (1.31 \pm 0.53 \pm 0.65) \times 10^{-4}$$

The number of events surviving various cuts for real data and Monte Carlo data are listed in Table 5 and the major sources of systematic error are listed in Table 6. The result obtained from this channel is consistant with the result obtained from γK^+K^-.

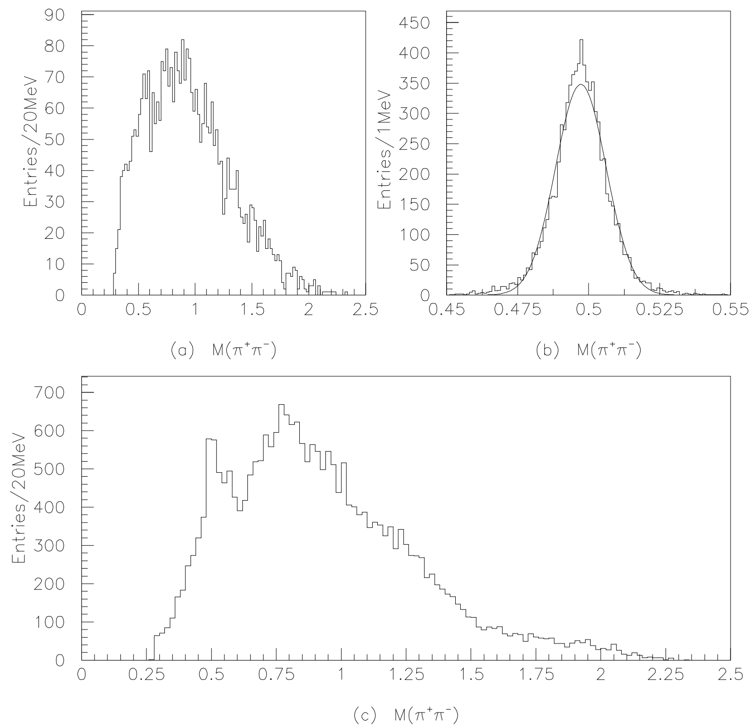


Figure 6: Invariant mass of $\pi^+\pi^-$in (a) $\gamma\pi^+\pi^-\pi^+\pi^-$ Monte Carlo (b) $\gamma f_J(1710) \rightarrow \gamma K_S^0 K_S^0 \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$ Monte Carlo (c) ψ' data.

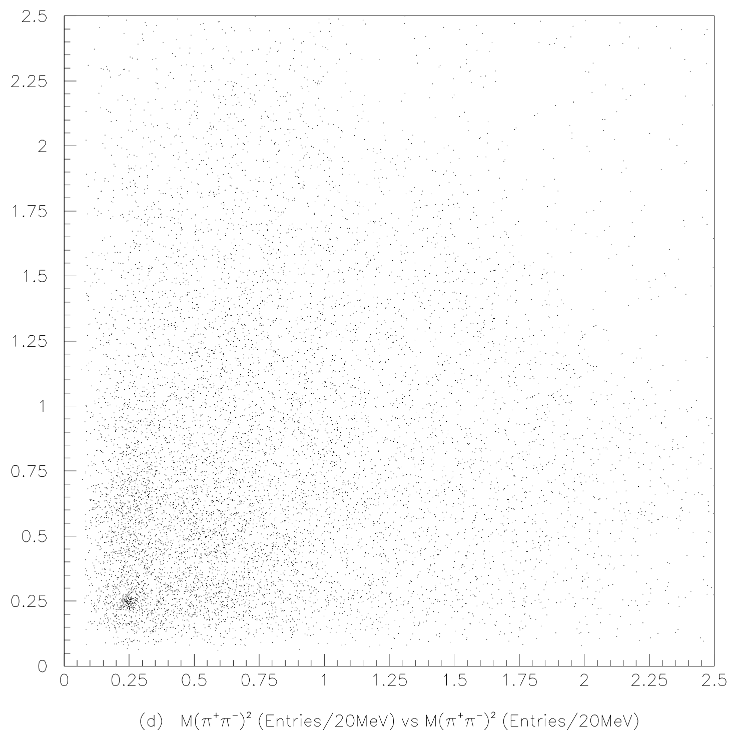
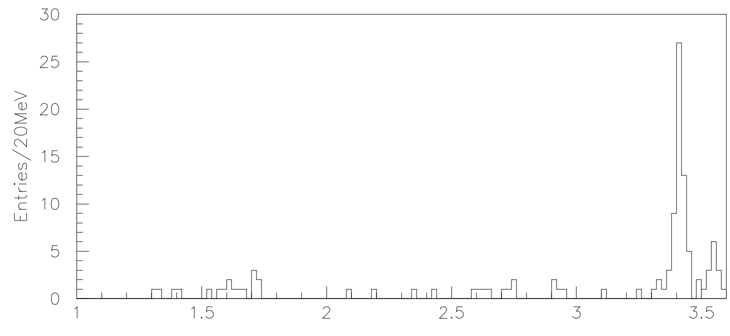


Figure 7: $M^2_{\pi^+\pi^-}$ vs. $M^2_{\pi^+\pi^-}$ in ψ' data.



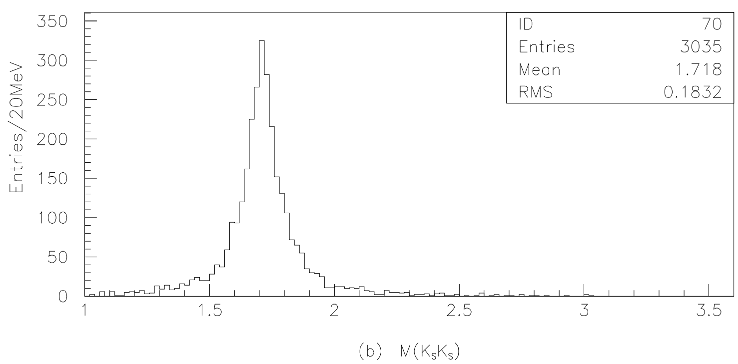


Figure 8: Invariant mass of $\pi^+\pi^-\pi^+\pi^-$ in (a) ψ' data (b) $\psi' \to \gamma\pi^+\pi^-\pi^+\pi^-$ phase space Monte Carlo.

4 Summary

In this analysis, we used the $\sim 3.6 \times 10^6$ ψ' data collected by the BES detector [4]and we studied the radiative decay processes of ψ' into $\gamma\pi^+\pi^-$,γK^+K^- and $\gamma K^0_S K^0_S$. Signals of $f_2(1270)$ and $f_J(1710)$ have been seen in $\psi' \to \gamma\pi^+\pi^-$ and γK^+K^- channels and the branching fractions of ψ' radiative decay into them have been measured as:

$$B(\psi' \to \gamma f_2(1270)) = (2.71 \pm 0.22 \pm 0.45) \times 10^{-4}$$

$$B(\psi' \to \gamma f_J(1710) \to \gamma K\bar{K}) = (1.04 \pm 0.15 \pm 0.18) \times 10^{-4}$$

From the $\gamma K^0_S K^0_S$ we also obtained a consistant result:

$$B(\psi' \to \gamma f_J(1710) \to \gamma K\bar{K}) = (1.31 \pm 0.53 \pm 0.65) \times 10^{-4}$$

Due to the strong QED background and lack of statistics, we have not tried to determinate the spin of $f_J(1710)$.

The ratioes of these branching fractions and those corresponding branching fractions in J/ψ decay are:

$$Q = \frac{B(\psi' \to \gamma f_2(1270))}{B(J/\psi \to \gamma f_2(1270))} = (19.6 \pm 1.6 \pm 3.3)\%$$

$$Q = \frac{B(\psi' \to \gamma f_J(1710) \to \gamma K\bar{K})}{B(J/\psi \to \gamma f_J(1710) \to \gamma K\bar{K})} = (10.7 \pm 2.0 \pm 2.3)\%$$

These results show that the theoretical prediction by the lowerst order QCD are followed in these radiative decay modes.

It should point out that although not fully accomplished by analysis memo, Li Xinhua and Bill Dunwoodie had made pioneer work in these area and their idea is adopted in this studying[5][6].

References

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