Observation of

$$\Psi(3686) -> e^{+} e^{-} \chi_{CJ} \ \ and \ \ \chi_{CJ} -> e^{+} e^{-} J/\Psi$$

JC98

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Object

Using 4.479×10^8 $\psi(3686)$ events collected with the BESIII detector, we search for the decays $\psi(3686) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^-J/\psi$, where $J = 0, 1, 2$. The decays $\psi(3686) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^-J/\psi$ are observed for the first time. The measured branching fractions are $\mathcal{B}(\psi(3686) \to e^+e^-\chi_{cJ}) = (11.7 \pm 2.5 \pm 1.0) \times 10^{-4}$, $(8.6 \pm 0.3 \pm 0.6) \times 10^{-4}$, $(6.9 \pm 0.5 \pm 0.6) \times 10^{-4}$ for $J = 0, 1, 2$, and $\mathcal{B}(\chi_{cJ} \to e^+e^-J/\psi) = (1.51 \pm 0.30 \pm 0.13) \times 10^{-4}$, $(3.73 \pm 0.09 \pm 0.25) \times 10^{-3}$, $(2.48 \pm 0.08 \pm 0.16) \times 10^{-3}$ for $J = 0, 1, 2$, respectively. The ratios of the branching fractions $\mathcal{B}(\psi(3686) \to e^+e^-\chi_{cJ})/\mathcal{B}(\psi(3686) \to \gamma\chi_{cJ})$ and $\mathcal{B}(\chi_{cJ} \to e^+e^-J/\psi)/\mathcal{B}(\chi_{cJ} \to \gamma J/\psi)$ are also reported. Also, the α values of helicity angular distributions of the e^+e^- pair are determined for $\psi(3686) \to e^+e^-\chi_{c1,2}$ and $\chi_{c1,2} \to e^+e^-J/\psi$.

Introduction

- The study of Electromagnetic Dalitz Decay(V-> Pl+l-, V=(Rho, omega, phi, psi) and P(pi0, eta, eta' chicj etc)), in which a virtual photon is internally converted into l+l- pair, plays an important role in revealing the structure of hadrons and the interaction between photons and hadrons.
- Such decays are widely observed in the light-quark meson sector.

  example- $\eta^{l} -> \gamma e^{+} e^{-}$ *or* $\eta^{l} -> \omega e^{+} e^{-}$ *or* $\Phi -> \eta e^{+} e^{-}$

- However, the analogous transition in carmonium decays have not yet been studied.
- Although the potential quark model has successfully described the lowlying charmonium states with high precisions, there are still puzzling discrepancies in the decay branching fractions

- Recently the BESIII experiment confirms that the contributions from the higher order multipole amplitudes in ψ(3686)-> γχcJ are small, the E1 contribution is dominant.
- Therefore, it is a great interest to measure the EM transition ψ(3686)-> e+e-χcJ and χcJ-> e+e-J/ψ.
- The EM Dalitz decays in charmonium transition, such as ψ(3686)-> e+e-χcJ -> e+e-J/ψ, have access to the EM transition form factor of these charmonium states.
- The EM Dalitz decays in charmonium transitions, such as ψ(3686)-> e+e-χcJ or χcJ->e+e-J/ψ, have access to the EM transition from factors (TFFs) of these charmonium states.
- The q^2 dependence of charmonium TFFs can provide additional information on the interactions between the charmonium states and the electromagnetic field, where q^2 is the square of the invariant mass of the e+e− pair, and serve as a sensitive probe to their internal structures.
- The q^2-dependent TFF can also serve as a useful probe for exotic hadron structures based on different models.

Data Taken

- The analysis uses a data sample of 4.479*10^8 ψ(3686) events taken at a centre of mass energy sqrt(s)= 3.686 GeV collected with the BESIII detector.
- In addition, a data sample corresponding to an integrated luminosity of 44/pb, taken at a centre of mass energy sqrt(s)=3.65 GeV, is used to estimate the background from continuum processes.
- Monte Carlo (MC) simulations are used to estimate the reconstruction efficiencies and study the backgrounds.The signal MC samples are generated using EVTGEN using a q^2-dependent decay amplitude based on the assumption of a pointlike meson, , and an angular distribution based on that observed in data.
- An MC sample of generic ψ(3686) decays, the so called "inclusive MC sample," is used for the background studies.
- The production of the ψ(3686) state is simulated by the KKMC generator.

- The known decay modes of the $\psi(3686)$ are simulated by EVTGEN according to the branching fractions reported in PDG, while the unknown modes are simulated using the LUNDCHARM model.
- Candidate events are required to have four charged tracks, with a sum of charges equal to zero, and at least one photon.
- The tracks with momentum larger than 1 GeV/c are assumed to be leptons from J/ψ decay. Otherwise, they are considered as electrons from the ψ' or χ_{cJ} decay.
- Leptons from the J/ψ decay with EMC energy larger than 0.8 GeV are identified as electrons, otherwise as muons.
- A study of the $\psi(3686)$ inclusive MC sample shows that, after applying the above selection criteria, the main background comes from $\psi(3686) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to \gamma J/\psi$ decays, where one photon converts into an e^+e^- pair in the detector material.
- To suppress this background, a photon-conversion finder is applied to reconstruct the photon-conversion vertex. The distance from the point of the reconstructed conversion vertex to the z axis, R_{xy}, is used to distinguish the photon conversion background from signal.
- With the requirement, the γ conversion background is negligible for the decays $\psi(3686) \to e^+e^-\chi_{cJ}$ and is at the few percent level for the decays $\chi_{cJ} \to e^+e^- J/\psi$.

- To remove the backgrounds from decays $\psi(3686) \to \eta/\pi0\ J/\psi$; $\eta/\pi0 \to \gamma e+e-$, which have the same final state as signal events, a requirement $0.16 < M(\gamma e+e-) < 0.50$ GeV/c2 is applied.
- By studying the data collected at sqrt(s)=3.65GeV, the contribution from the continuum process is found to be negligible.
- Figure 1 shows the scatter plot of $M(\gamma J/\psi)$ versus $M(e+e-J/\psi)$ for the selected events from data; the corresponding one-dimensional projections are shown in Figure 2.

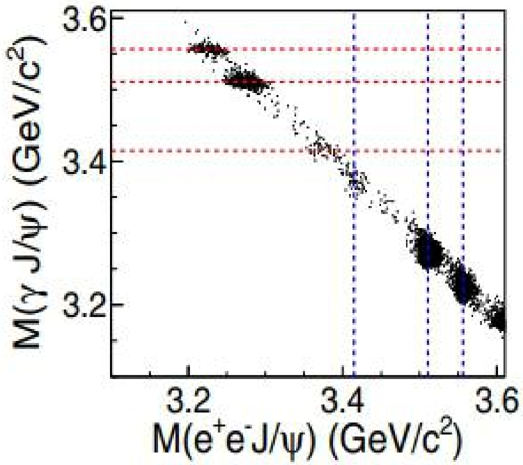

FIG. 1. Scatter plot of $M(\gamma J/\psi)$ versus $M(e^+e^-J/\psi)$ for data. The horizontal red dashed lines and vertical blue dashed lines indicate the positions of the χ_{cJ} masses in the $M(\gamma J/\psi)$ and $M(e^+e^-J/\psi)$ distributions, respectively.

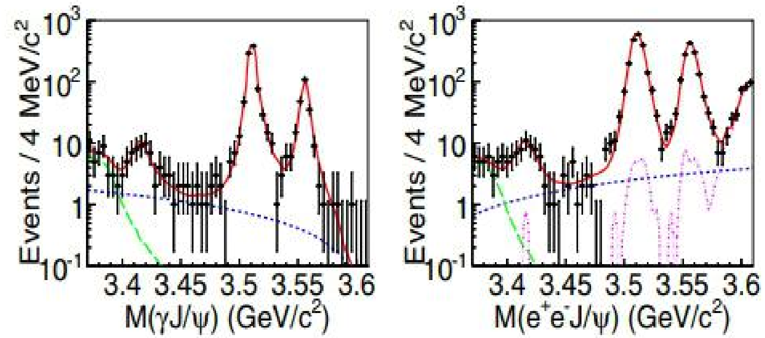

FIG. 2. Data (points with error bars) distributions of (left) $M(\gamma J/\psi)$ and (right) $M(e^+e^-J/\psi)$. The red solid curve is the overall fit result, the green long-dashed curve is for the background (left) $\psi(3686) \to \gamma\chi_{c0}$, $\chi_{c0} \to e^+e^-J/\psi$ and (right) $\psi(3686) \to e^+e^-\chi_{c0}$, $\chi_{c0} \to \gamma J/\psi$, the blue dashed curve is for QED background, and the pink dashed-dotted curve in right plot is for the backgrounds from $\psi(3686)$ decays.

Fitting Results

- The fit results are shown in Fig. 2 and the corresponding signal yields are summarized in Table I. For the six observed decay modes, the statistical significance of the yields are all larger than 5 standard deviations.

TABLE I. Signal yields, detection efficiencies, the branching fractions, and the ratios of the branching fractions. Here, the first uncertainty is statistical and the second systematic.

Mode	Yields	Efficiency(%)	Branching fraction	$\mathcal{B}(\psi(3686)\to e^+e^-\chi_{cJ})/$ $\mathcal{B}(\psi(3686)\to\gamma\chi_{cJ})$	$\mathcal{B}(\chi_{cJ}\to e^+e^-J/\psi)/$ $\mathcal{B}(\chi_{cJ}\to\gamma J/\psi)$
$\psi(3686)\to e^+e^-\chi_{c0}$	48 ± 10	6.06	$(11.7\pm2.5\pm1.0)\times10^{-4}$	$(9.4\pm1.9\pm0.6)\times10^{-3}$	$\cdots$
$\psi(3686)\to e^+e^-\chi_{c1}$	873 ± 30	5.61	$(8.6\pm0.3\pm0.6)\times10^{-4}$	$(8.3\pm0.3\pm0.4)\times10^{-3}$	$\cdots$
$\psi(3686)\to e^+e^-\chi_{c2}$	227 ± 16	3.19	$(6.9\pm0.5\pm0.6)\times10^{-4}$	$(6.6\pm0.5\pm0.4)\times10^{-3}$	$\cdots$
$\chi_{c0}\to e^+e^-J/\psi$	56 ± 11	6.95	$(1.51\pm0.30\pm0.13)\times10^{-4}$	$\cdots$	$(9.5\pm1.9\pm0.7)\times10^{-3}$
$\chi_{c1}\to e^+e^-J/\psi$	1969 ± 46	10.35	$(3.73\pm0.09\pm0.25)\times10^{-3}$	$\cdots$	$(10.1\pm0.3\pm0.5)\times10^{-3}$
$\chi_{c2}\to e^+e^-J/\psi$	1354 ± 39	11.23	$(2.48\pm0.08\pm0.16)\times10^{-3}$	$\cdots$	$(11.3\pm0.4\pm0.5)\times10^{-3}$

$$\mathcal{B}=\frac{N_{\rm sig}}{N_{\psi(3686)}\epsilon\mathcal{B}_{\rm radiative}\mathcal{B}(J/\psi\to l^+l^-)}, \qquad (1)$$

where $N_{\rm sig}$ is the corresponding number of signal events extracted from the fit, $N_{\psi(3686)}$ is the total number of $\psi(3686)$ events, ϵ is the selection efficiency determined from the signal MC samples, $\mathcal{B}_{\rm radiative}$ is the branching fraction of the radiative transitions $\psi(3686)\to\gamma\chi_{cJ}$ or $\chi_{cJ}\to\gamma J/\psi$, and $\mathcal{B}(J/\psi\to l^+l^-)$ is the decay branching fraction of $J/\psi\to l^+l^-$. All the branching fractions used are taken from Ref. [3]. The resultant branching fractions of $\psi(3686)\to e^+e^-\chi_{cJ}$ and $\chi_{cJ}\to e^+e^-J/\psi$ are listed in Table I.

- The systematic uncertainties for the branching fraction measurement arise from the following sources: track reconstruction, photon detection, kinematic fitting, J/ψ mass criteria, M(γe+e−) requirement, γ conversion vetoing, fit procedure, angular distributions, the total number of ψ(3686) events, and the branching fractions of the cascade decays.
- The uncertainty associated with the J/ψ mass requirement is 1.0%, which is determined by studying a control sample of ψ(3686) → ηJ/ψ, η → γγ (where one γ undergoes conversion to an e+e− pair) or η → γe+e− decays. The systematic uncertainty related to the M(γe+e−) interval used is studied by varying the edges of the interval by 5 MeV/c2. The largest difference with the nominal value is taken as the systematic uncertainty from this source.
- To study the systematic uncertainty related to the γ conversion background veto, we compare the efficiencies of γ conversion veto between data and the MC simulation in control samples of ψ(3686) → γχc1;2, χc1;2 → e+e−J/ψ decays. The efficiency of the γ conversion veto is the ratio of the signal yields determined by fitting the M(e+e−) distribution with and without the γ conversion veto applied. A relative difference between data and simulation of 1.4% is found and assigned as the systematic uncertainty.
- The total number of ψ(3686) events is measured to within 0.7% by using the inclusive hadronic events [M. Ablikim et al. (BESIII Collaboration), Chin. Phys. C 37,
- 063001 (2013) and Using the same method as in Ref. [14], the total number of ψ(3686) events taken at 2009 and 2012 is measured to be (4.479 +- 0.029) × 108]. The uncertainties of the branching fractions in the cascade decays are taken from Ref. [C. Patrignani et al. (Particle Data Group), Chin. Phys. C 40, 100001 (2016)].
- All the uncertainies has been discussed in the paper in detail.

The effect of other potential systematic uncertainty sources are considered, such as uncertainties on the generated q distributions, the trigger efficiency, and the simulation of the event time, but are all found to be negligible. Table II summarizes all individual systematic uncertainties, and the overall uncertainties are the quadrature sums of the individual ones, assuming they are independent.

TABLE II. Summary of systematic uncertainties (in %).

	$\psi(3686) \to e^+e^-\chi_{cJ}$			$\chi_{cJ} \to e^+e^-J/\psi$		
	χ_{c0}	χ_{c1}	χ_{c2}	χ_{c0}	χ_{c1}	χ_{c2}
Tracking	4.0	4.0	4.0	4.0	4.0	4.0
Photon	1.0	1.0	1.0	1.0	1.0	1.0
Kinematic fit	1.6	1.4	1.4	1.8	2.2	2.4
J/ψ mass window	1.0	1.0	1.0	1.0	1.0	1.0
$M(\gamma e^+e^-)$	2.7	1.2	1.0	0.7	2.2	0.4
γ conversion vetoing	1.4	1.4	1.4	1.4	1.4	1.4
Fit range	2.2	0.2	0.3	4.7	0.1	0.2
Signal shape	0.4	0.1	0.1	2.2	0.2	0.5
Background shape	2.2	0.2	0.3	0.1	0.1	0.2
Angular distribution	3.9	2.1	3.3	3.6	1.6	1.0
Number of $\psi(3686)$	0.7	0.7	0.7	0.7	0.7	0.7
Branching fractions	4.8	3.6	5.5	2.8	3.3	3.5
sum	8.9	6.5	8.1	8.5	6.6	6.3

Summary

- In summary, using a data sample of 4.479×108 $\psi(3686)$ events collected with the BESIII detector operating at the BEPCII collider, the decays $\psi(3686) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^-J/\psi$ are observed for the first time, and the corresponding branching fractions are measured and the values are given in Table I.
- The ratios of branching fractions $B(\psi(3686)\to e^+e^-\chi_{cJ})/B(\psi(3686)\to\gamma\chi_{cJ})$ and $B(\chi_{cJ}\to e^+e^-J/\psi)/B(\chi_{cJ}\to\gamma J=\psi)$ are also obtained by incorporating the BESIII results of the product of branching fractions $B(\psi(3686) \to \gamma\chi_{cJ})B(\chi_{cJ} \to \gamma J/\psi)$ as listed in Table I.
- The common systematic uncertainties related to efficiency and branching fractions cancel in the calculation.
- The measured q^2 distributions are consistent with those of the signal MC simulation based on the assumption of a pointlike meson.
- This first observation of the q2-dependent charmonium EM Dalitz transitions can help understand the discrepancy between the experimental measurements **[3]** and the theoretical predictions **[4–7]** of the $\psi(3686) \to \gamma\chi_{cJ}$ branching fractions. The experimental methods applied here for the first study of charmonium Dalitz decays are likely to be of use for similar studies of the X(3872).
- It is hoped that this experimental work will spur new theoretical development on the use of charmonium Dalitz decays to address questions such as the nature of exotic charmonium.

[3] and [4-7]: for the theoretical and experimental measurements.

Questions

- Xin's Question: why the "q^2-dependent TFF" can be served as a probe for exotic hadron structures based on different models?
- EM Dalitz decays in charmonium transitions have access to the EM transition Form Factor(TFF's). In other words, The transition states have the access to the EM TFF's.

The q^2 dependence of charmonium TFF's can provide additional information on the interactions between the charmonium state and electromagnetic field, where q^2 is the invariant mass of e+e- pair, and serves as a sensitive probe to their internal structures. Furthermore, the q^2 dependent TFF can possibly distinguish the transition mechanism based on the ccbar scenario and also the other soultions which alter the simple quark model picture.

Hence, the author claims that the q^2-dependent TFF can also serve as a useful probe fro exotic hadron structures based on different models.In the future, the intrinsic structure of X(3872) can be well extracted by coparing the experimental measurement of q^2 dependence of TFF with different model calculation. The nature of X(3872), namely, whether it is a compact charmonium, multiquark state with quark clustering, or hadronic molecule can possibly be disentangled by the q^2 dependence of its TFF.

- Yuhang's Question: On page3, it says:" The unknown modes are simulated using the LUNDCHARM model." What's LUNDCHARM? How to filter out unknown parts from the generated cases or LUNDCHARM can only generate unknown cases.
- You have the answer in your second line of the question. Yes, LUNDCHARM is an event generator for J/psi and psi(2S) decay.

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Event generator for J/ψ and $\psi(2S)$ decay

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We have developed a Monte Carlo generator for simulating charmonium J/ψ and $\psi(2S)$ inclusive decay. In the model, charmonium decay via gluons is described by the QCD partonic theory, and the partonic hadronization is handled by the LUND model. Extended C- and G-parity conservation are assumed and abnormal suppression effects of charmonium decay are included. This model reproduces the properties of hadronic events in the charmonium inclusive decay, such as the branching ratios of hadronic resonance, the ratios of stable hadrons and the radiative products, and as the global properties of hadronic events.

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- The LUNDCHARM model can generate all the cases i.e. known and unknown both the cases. In the paper, they have only taken the unknown cases from this generator.

- Back-up:(XIn's Question)

Book: ELECTROMAGNETIC DECAYS OF LIGHT MESONS

The differential cross-section for the scattering of an electron by a particle with a specific space structure can be written in the form

$$\mathrm{d}\sigma/\mathrm{d}\boldsymbol{q}^2 = [\mathrm{d}\sigma/\mathrm{d}\boldsymbol{q}^2]_{\text{pointlike}}[F(\boldsymbol{q}^2)]^2 . \tag{1.1}$$

The function $F(\boldsymbol{q}^2)$ is said to be the form factor of a particle. The form factor can be found by comparing experimental data with the result of a computation of the differential cross-section for the scattering of an electron by a pointlike charged particle, $[\mathrm{d}\sigma/\mathrm{d}\boldsymbol{q}^2]_{\text{pointlike}}$. The form factor gives an exhaustive characterization of the spatial distribution of charge for an extended object.* In the limit of small momentum transfer, i.e., for $\boldsymbol{q}^2 \ll 1/a^2$, we find $F(\boldsymbol{q}^2) \approx 1$. Conversely, if $\boldsymbol{q}^2 \gg 1/a^2$, then $F(\boldsymbol{q}^2)$ falls off rapidly and becomes much less than unity. Calculations show that, at low momentum transfers, the quantity $b = \mathrm{d}F(\boldsymbol{q}^2)/\mathrm{d}(\boldsymbol{q}^2)|_{\boldsymbol{q}^2=0}$, which is usually called the slope of the form factor, is determined by the radius of the distribution of the particle's electric charge:

$$F(\boldsymbol{q}^2) = 1 - \tfrac{1}{6}\boldsymbol{q}^2 a^2 \qquad \text{and} \qquad b = -\tfrac{1}{6}a^2 . \tag{1.2}$$

The analysis of high-energy electron scattering by real particles (e.g. protons or neutrons) is more complicated, although the pattern remains qualitatively the same. The factors that now become important are the spin and the (related to it) magnetic moment of the scattering particle. The magnetic moment of a hadron has also a spatial distribution which is characterized by its own form factor. A description of the electromagnetic structure of protons (and neutrons), which are spin-1/2 particles, requires that two different form factors, one electric and one magnetic, be introduced.

In the framework of a consistent relativistic description of the scattering of an electron by a finite-mass hadron it is not possible any more to establish a simple relation between the form factor of the hadron and the spatial distribution of its charge density. Nevertheless, form factors carry, as in the nonrelativistic case, a complete information on the electromagnetic structure of a particle and represent the directly measurable characteristics of this structure with which the current theory works.

- Suyu's Question:

In this Letter, we report the observation of the EM Dalitz decays $\psi(3686) \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^-J/\psi$ by analyzing the cascade decays $\psi(3686) \to e^+e^-\chi_{cJ}$, $\chi_{cJ} \to \gamma J/\psi$ and $\psi(3686) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to e^+e^-J/\psi$, respectively.

Why can they do in this way? I don't think they are exactly the same process.

- Answer: I'm sorry because I didn't understand the question correctly.

They are analyzing cascade decay process and both have same final state.
In the first manner psi(3686)->e+e- chicj and chicj->gamma J/psi
secondly psi(3686)->gamma chicj and chicj->e+e- J/psi.

Thank You!!!