SOME COMMENTS ON THE STATES BETWEEN THE ψ AND ψ '

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ABSTRACT

A spin-parity assignment is made for the four even charge conjugation states now probably observed between the ψ and ψ' . Consequences for the model of the new mesons as bound states of a new heavy quark and its corresponding antiquark are then commented upon.

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A new situation with respect to the spectroscopy of the new particles has emerged with the probable observation¹ of four states formed via gamma ray decays of the ψ '(3684). The χ (3530), previously found² as a broader "object" in hadronic decay modes, is now resolved¹ into separate components at ~ 3500 and ~ 3550 MeV. These are presumably identifiable with states at essentially the same mass values seen decaying into $\gamma \psi$ (3095): we call them³ χ (3545) and χ (3505) \equiv P_c.^{4,5} Another state, χ (3455), very likely exists and is seen decaying¹ into $\gamma \psi$, but has no clearly observed hadronic modes. The χ (3410) on the other hand is found^{1,2} decaying in many hadronic modes, and is indicated¹ by a monochromatic line in the inclusive gamma ray spectrum⁶ of the ψ ', but is only hinted at in the $\gamma \psi$ mode.^{1,4}

In the picture of the ψ , ψ' ,... as bound states of a new heavy quark and its corresponding antiquark, these even charge conjugation states are most welcome. In number they correspond exactly with the p-wave states $({}^{3}P_{2}, {}^{3}P_{1}, {}^{3}P_{0})$ and the pseudoscalar partner $({}^{1}S_{0}')$ of the ψ' expected from orbital and radial excitation of the ground state ψ and its pseudoscalar partner, X(2.8?).⁴

In the following, we will stay within the confines of this conventional picture, although other theoretical options may well be viable. In particular, we assume all four χ states exist and are the ${}^{3}P_{0,1,2}$ and ${}^{1}S_{0}$ ' heavy quark - antiquark bound states and explore the consequences, qualitatively and quantitatively, of making this correspondence.

We begin by adding to our list of experimental findings two "quasi-facts" which are strongly indicated phenomenologically, but not completely confirmed:

(1) The χ (3410) has $J^{PC} = 0^{++}$. The decay into $\pi^+\pi^-$ and K^+K^- demands $J^{PC} = (\text{even})^{++}$ and within the p-wave states only 0^{++} and 2^{++} are then possible.

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The photon angular distribution for $\psi' \rightarrow \gamma 0^+$ must be $1 + \cos^2 \theta$, which is consistent with the observed distribution¹ for χ (3410). This ordering of the 0^+ and 2^+ mesons is consistent with the old spectroscopy and with the ordering of the p-wave quark-antiquark states in reasonable potential models.

(2) The branching ratio for $\psi'(3684) \rightarrow \gamma \chi(3455)$ is $\leq 10\%$. If this branching ratio were larger than 10% then the monochromatic photon line would have been easily seen in the inclusive gamma ray spectrum.^{1,6} Furthermore the $\chi(3455)$ would then have to decay predominantly into channels other than $\gamma \psi$ (since¹ BR($\psi' \rightarrow \gamma \chi(3455) \rightarrow \gamma \gamma \psi$) $\approx 1\%$), and it becomes very difficult to see how it could have escaped having a prominent decay in <u>some</u> hadronic channel, as do the other χ 's.

Even with the 0⁺, 1⁺, and 2⁺ p-wave states arranged to have increasing mass, starting with 0⁺⁺ at 3410 MeV, there are still three possible ways to assign spins and parities to the remaining states, corresponding to putting the pseudoscalar at 3455, 3505 or 3545 MeV, respectively. The latter two possibilities may be rejected on several grounds. First, χ (3455) would then have to be the 1⁺ state and the rate for $\psi' \rightarrow \gamma 1^+$ is calculable from that for $\psi' \rightarrow \gamma 0^+$ within the model of the particles as bound states of heavy quarks where these are related electric dipole transitions.^{7,8} Given the observation¹ of a 5 to 10% branching ratio for $\psi' \rightarrow \gamma \chi$ (3410), a 1⁺ assignment for χ (3455) would mean $\psi' \rightarrow \gamma \chi$ (3455) with a branching ratio of 10-20%. This contradicts our "quasi-fact" (2). Second, both the states at 3505 and 3550 are known to have important decays into hadrons. If either is the pseudoscalar partner (η_c) of the ψ' , then the pseudoscalar partner (η_c) of the ψ should have similar decays with at least as large a branching fraction.⁹ Furthermore, we expect $\Gamma(\psi' \rightarrow \gamma \eta_c') \approx \Gamma(\psi \rightarrow \gamma \eta_c)$, assuming equal phase space.¹⁰ In branching

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fraction the latter decay then would be $\Gamma(\psi' \rightarrow \text{all})/\Gamma(\psi \rightarrow \text{all}) \approx 3.3$ times greater than the former. Therefore the branching ratio for $\psi \rightarrow \gamma \eta_c \rightarrow \gamma + \text{hadrons}$ should be significantly stronger than that for $\psi' \rightarrow \gamma \eta_c' \rightarrow \gamma + \text{hadrons}$. But $\psi' \rightarrow \gamma \chi (3505) \rightarrow \gamma + \text{hadrons or } \psi' \rightarrow \gamma \chi (3550) \rightarrow \gamma + \text{hadrons are clearly seen}$, while neither the monochromatic gamma ray line from the ψ nor $\psi \rightarrow \gamma \eta_c \rightarrow \gamma + \text{hadrons is seen}$. We conclude that the most plausible assignment¹¹ of states is:

$$\chi (3545) : {}^{3}P_{2}, J^{PC} = 2^{++}$$

$$\chi (3505) : {}^{3}P_{1}, J^{PC} = 1^{++}$$

$$\chi (3455) : {}^{1}S_{0}', J^{PC} = 0^{-+}$$

$$\chi (3410) : {}^{3}P_{0}, J^{PC} = 0^{++}$$

The splitting of the p-wave states is roughly an order of magnitude larger than would be predicted¹² by assuming the spin dependent forces arise only from (Coulomb-like) colored gluon exchange at short distances in the framework of an asymptotically free gauge theory of strong interactions. Moreover, we have the ratio

$$\frac{M(2^{+}) - M(1^{+})}{M(1^{+}) - M(0^{+})} \approx \frac{0.40}{0.95} = 0.47 .$$
 (1)

With just an $\vec{L} \cdot \vec{S}$ term in the effective Hamiltonian, one expects a value of 2. A more sophisticated analysis, ¹³ reducing the relativistic interaction due to an effective gluon exchange¹⁴ to non-relativistic form in analogy to treatments of positronium, leads one to expect contributions to the p-wave mass splittings from both $\vec{L} \cdot \vec{S}$ and tensor operator terms in the effective Hamiltonian. It has been pointed out¹³ that with an arbitrary combination of Coulomb and linear (confining) potentials binding the quark and antiquark together, the ratio in Eq. (1) should lie between 0.8 and 1.4. The observed value lies outside this

range, presumably indicating the inadequacy of such an approach to the problem. The discrepancy is too large to be resolved by including the effect of mixing with virtual continuum pairs, which is only expected¹⁵ to shift the relative masses by ~ 15 MeV.

We may proceed further by using the information on the relative rates for $\psi' \rightarrow \gamma \chi \rightarrow \gamma \gamma \psi$ for each of the p-states. First we note that

$$\frac{\Gamma(2^{+} \rightarrow \text{all})}{\Gamma(1^{+} \rightarrow \text{all})} = \frac{BR(\psi^{+} \rightarrow \gamma 1^{+} \rightarrow \gamma \gamma \psi)}{BR(\psi^{+} \rightarrow \gamma 2^{+} \rightarrow \gamma \gamma \psi)} \frac{\Gamma(2^{+} \rightarrow \gamma \psi)}{\Gamma(1^{+} \rightarrow \gamma \psi)} \frac{\Gamma(\psi^{+} \rightarrow \gamma 2^{+})}{\Gamma(\psi^{+} \rightarrow \gamma 1^{+})}$$
(2)

The first factor is just the ratio of observed $\psi' \rightarrow \gamma \gamma \psi$ events (corrected for detection efficiency) proceeding through the 1⁺ and 2⁺ intermediate states, respectively, which is experimentally¹ \approx 3. The latter two factors are both computable within the context of the picture of the mesons as bound states of heavy quarks and antiquarks where the <u>relative</u> rates⁸ for $\psi' \rightarrow \gamma^3 P_J$ and the <u>relative</u> rates¹⁶ for ${}^3P_J \rightarrow \gamma \psi$ are predicted. With our assignment of states we compute¹⁷ from (2) and the experimental ratio of $\gamma \gamma \psi$ events,

$$\frac{\Gamma(2^{+} \rightarrow \text{all})}{\Gamma(1^{+} \rightarrow \text{all})} = \frac{\Gamma(2^{+} \rightarrow \gamma \psi) + \Gamma(2^{+} \rightarrow \text{hadrons})}{\Gamma(1^{+} \rightarrow \gamma \psi) + \Gamma(1^{+} \rightarrow \text{hadrons})} \approx 3.1 .$$
(3)

Since our assumption of electric dipole transitions implies $\Gamma(2^+ \rightarrow \gamma \psi) = 1.3 \Gamma(1^+ \rightarrow \gamma \psi)$, we find from Eq. (3):

$$\frac{\Gamma(2^{+} \rightarrow \text{hadrons})}{\Gamma(1^{+} \rightarrow \text{hadrons})} \simeq 3.1 + 1.8 \frac{\Gamma(1^{+} \rightarrow \gamma \psi)}{\Gamma(1^{+} \rightarrow \text{hadrons})}.$$
(4)

A similar analysis may be performed replacing the 2⁺ state with the 0⁺ state at 3410 MeV. If we take seriously a candidate event for $\psi' \rightarrow \gamma 0^+ \rightarrow \gamma \gamma \psi$ from DESY^{4, 18} and one from the magnetic detector¹ at SPEAR (corresponding to a branching ratio $\approx 1/4\%$), we have

$$\frac{\mathrm{BR}(\psi' \to \gamma 1^{+} \to \gamma \gamma \psi)}{\mathrm{BR}(\psi' \to \gamma 0^{+} \to \gamma \gamma \psi)} \approx 12 .$$

The analog of Eq. (4), using the same assumptions, then is

$$\frac{\Gamma(0^+ \to \text{hadrons})}{\Gamma(1^+ \to \text{hadrons})} \simeq 6.5 + 6.0 \frac{\Gamma(1^+ \to \gamma \psi)}{\Gamma(1^+ \to \text{hadrons})} .$$
(5)

Now BR($\psi' \rightarrow \gamma 1^+ \rightarrow \gamma \gamma \psi$) $\approx 3\%$.^{1,5} while the 5 to 10% branching ratio¹ for $\psi' \rightarrow \gamma 0^+$ and the assumption of electric dipole transitions implies that $4.5\% < BR(\psi' \rightarrow \gamma 1^+) < 9\%$ (with a central value of $\approx 6\%$). Therefore the ratio

$$\frac{\Gamma(1^+ \rightarrow \gamma \psi)}{\Gamma(1^+ \rightarrow \text{hadrons})} ,$$

which appears in both Eqs. (4) and (5) is at least 0.5 (and more likely \sim 1). As a result, from Eq. (4),

$$\frac{\Gamma(2^+ \rightarrow \text{hadrons})}{\Gamma(1^+ \rightarrow \text{hadrons})} \gtrsim 4,$$

and more likely is \approx 5, while from Eq. (5),

$$\frac{\Gamma(0^+ \rightarrow \text{hadrons})}{\Gamma(1^+ \rightarrow \text{hadrons})} \gtrsim 9$$

and more likely is ≈ 12 . If instead of BR($\psi' \rightarrow \gamma 0^+ \rightarrow \gamma \gamma \psi$) $\approx 1/4\%$, we take BR($\psi' \rightarrow \gamma 0^+ \rightarrow \gamma \gamma \psi$) $\leq 1/2\%$, the previous upper limit from SPEAR⁵, then $\Gamma(0^+ \rightarrow hadrons)/\Gamma(1^+ \rightarrow hadrons) \gtrsim 5$.

While improvements in the measurements of $\psi' \rightarrow \gamma^3 P_J \rightarrow \gamma \gamma \psi$ are obviously needed, we believe that the qualitative point is already established: both the 0⁺ and 2⁺ states have absolute decay widths into hadrons many times that of the 1⁺ state. This is in qualitative accord with the picture that such hadronic decays for C = + states proceed via two massless (colored) vector 19 gluons. Since a spin one state cannot decay into two massless vector particles, the 1⁺ state should have very much suppressed decays into hadrons. An investigation of the decay of the 1⁺ state by Barbieri et al. ²⁰ has shown a singular binding dependence (in the weak binding limit) for the decay into one massless and one massive gluon (coupled to a qq pair). They find quantitatively that¹⁹ $\Gamma(2^+ \rightarrow \text{hadrons}) : \Gamma(1^+ \rightarrow \text{hadrons}), \Gamma(0^+ \rightarrow \text{hadrons}) = 4 : \approx 1 : 15$. This is certainly qualitatively similar to our results and even quantitatively consistent considering experimental uncertainties.

Note that although $\Gamma(2^+ \rightarrow \text{hadrons}) \approx 5 \Gamma(1^+ \rightarrow \text{hadrons})$ we still expect $BR(\psi' \rightarrow \gamma 2^+ \rightarrow \gamma + \text{hadrons})$ to be comparable to $BR(\psi' \rightarrow \gamma 1^+ \rightarrow \gamma + \text{hadrons})$. In fact, their ratio is expected to be⁸

$$\frac{BR(\psi' \rightarrow \gamma 2^{+} \rightarrow \gamma + hadrons)}{BR(\psi' \rightarrow \gamma 1^{+} \rightarrow \gamma + hadrons)} = \frac{\Gamma(\psi' \rightarrow \gamma 2^{+})}{\Gamma(\psi' \rightarrow \gamma 1^{+})} \cdot \frac{BR(2^{+} \rightarrow hadrons)}{BR(1^{+} \rightarrow hadrons)}$$

$$= 0.79 \frac{BR(2^{+} \rightarrow hadrons)}{BR(1^{+} \rightarrow hadrons)}.$$
(6)

While the observed BR($\psi' \rightarrow \gamma 2^+ \rightarrow \gamma \gamma \psi$) $\approx 1\%$ and a calculated⁸ BR($\psi' \rightarrow \gamma 2^+$) $\approx 5\%$ leads us (allowing for experimental uncertainty) to $10\% \leq BR(2^+ \rightarrow \gamma \psi) \leq 30\%$ and hence $70\% \leq BR(2^+ \rightarrow hadrons) \leq 90\%$, a similar argument leads us to $30\% \leq BR(1^+ \rightarrow hadrons) \leq 60\%$. Thus, the right hand side of Eq. (6) should lie roughly between 1.0 and 2.4. If a particular channel, e.g., $4\pi^{\pm}$, $\pi^+\pi^-$ K⁺K⁻, is the same proportion of all hadronic decays for both the 1^+ and 2^+ states, we then expect roughly equal (but favoring the 2^+ state) 1^+ and 2^+ peaks in a plot of number of events <u>vs</u>. invariant mass for events with a missing gamma ray in ψ' decays. This explains why " χ (3530)" appeared (with insufficient resolution) as a broad "state" in hadronic decays – both χ (3505) and χ (3545) have comparable contributions to various hadronic channels giving the impression of a broader state centered between them. If $BR(\psi' \rightarrow \gamma 2^+ \rightarrow \gamma + hadrons)$ had been much greater than $BR(\psi' \rightarrow \gamma 1^+ \rightarrow \gamma + hadrons)$, then only a single narrow peak at 3545 MeV would have been seen previously in hadronic decays.

We now turn our attention to the state at 3455 MeV, which we have taken tentatively to be the pseudoscalar partner of the ψ '. It is observed¹ decaying into $\gamma \psi$, with BR($\psi' \rightarrow \gamma \chi$ (3455) $\rightarrow \gamma \gamma \psi$) $\approx 1\%$.

But we also have a constraint on $\Gamma(\chi(3455) \rightarrow \gamma \psi)$. The gamma ray decay of the ψ ' into the pseudoscalar partner of the ψ has the same (magnetic dipole) matrix element if we take them as s-wave quark-antiquark bound states. Taking the pseudoscalar partner of the ψ to be the X(2.8), we find using p³ phase space,

$$\Gamma(\chi(3455) \rightarrow \gamma \psi) \simeq 0.25 \ \Gamma(\psi' \rightarrow \gamma X) \ . \tag{7}$$

Experimentally, ²¹ $\Gamma(\psi' \rightarrow \gamma X) < 4.5 \text{ keV}$. Therefore

$$\Gamma(\chi (3455) \rightarrow \gamma \psi) \leq 1.1 \text{ keV}.$$
(8)

However, $\gamma \psi$ must be at least a 10% mode of χ (3455), for otherwise $\gamma \chi$ (3455) becomes more than a 10% mode of the ψ ', violating our "quasi-fact" (2). Therefore we conclude

$$\Gamma(\chi(3455) \rightarrow \text{all}) \leq 11 \text{ keV}! \tag{9}$$

Even if we drop the X(2.8) as the pseudoscalar partner of the ψ and just demand that it lie below the ψ mass and also allow $\gamma \psi$ to be only a 5% mode of χ (3455), we still have²²

$$\Gamma(\chi (3455) \rightarrow \text{all}) \leq 70 \text{ keV}. \tag{10}$$

This is a disaster for the two gluon annihilation picture of hadronic decays, which with χ (3455) the pseudoscalar partner of the ψ ', would have ^{7,19}

$$\Gamma(\chi (3455) \rightarrow \gamma \gamma) \simeq \frac{4}{3} \Gamma(\psi' \rightarrow e^+ e^-) = 2.8 \text{ keV}, \qquad (11)$$

and the two gluon width (i.e. hadronic width) ~ 10^3 times this. Our upper limit is about two orders of magnitude smaller; i.e. we get tens of keV instead of several MeV. Notice that this conclusion is actually independent of whether we take χ (3455), χ (3505) or χ (3545) as the pseudoscalar partner of the ψ' : all have substantial branching ratios into $\gamma \psi$ and a similar limit on their total width holds no matter which is the pseudoscalar.²³

Another independent argument indicates serious difficulty for the χ (3455) being the η_c ' and decaying into hadrons via annihilation into gluons. Based on the absence of observed hadronic modes¹, $\Gamma(\chi(3455) \rightarrow \text{hadrons})$ is very likely to be no more than²⁴ a few times $\Gamma(\chi(3455) \rightarrow \gamma\psi)$. But the inhibited magnetic dipole transition from a radial excitation to the ground state, $\eta_c' \rightarrow \gamma\psi$, should be smaller^{7,15} for a system of heavy quarks than the electric dipole decays, $\psi' \rightarrow \gamma\chi$, which are now known experimentally to have widths up to $\approx 20 \text{ keV}$. Therefore, $\Gamma(\chi(3455) \rightarrow \text{hadrons})$ is expected to be at most in the range of several tens of keV, which again is in serious disagreement with a few MeV as expected in the gluon annihilation picture.

We are thus driven theoretically to consider the possibility that $\chi(3455) \equiv \eta_c$, the pseudoscalar partner of the ψ rather than the ψ '. Bounds (9) and (10) then evaporate, but the situation still appears incompatible with the gluon annihilation picture: one must face $\gamma \psi$ being a non-negligible mode of $\chi(3455)$ and ask why no clear hadronic decays are yet seen even though their total width is supposed to be several MeV. And this is aside from the mass difference of the pseudoscalar and the corresponding vector state being ~ 350 MeV, which is not only surprisingly large but of the wrong sign compared to naive expectation. In summary, we have seen that the four even charge conjugation states between ψ and ψ' fit very well qualitatively into the general picture of the new mesons being bound states of a new quark and its corresponding antiquark. They exactly fill up the expected ${}^{3}P_{0}$, ${}^{3}P_{1}$, ${}^{3}P_{2}$ and ${}^{1}S_{0}$ ' slots expected in such a picture, and we have suggested an assignment of spins and parities on this basis.

What does not work so well is the picture of heavy non-relativistic quarks in a simple potential. In particular, one has a mass splitting of the ³P states which fits no combination of Coulomb, linear, and harmonic potentials when the problem is treated in analogy with that for positronium.

Even more contradictory is the comparison with experiment when the picture of bound heavy quarks is married with that of hadronic decays proceeding through annihilation into colored vector gluons. For the ³P states we have found evidence that the relative rates are at least in qualitative accord with the data. But if χ (3455) is established, then it should be the pseudoscalar and its width into hadrons is too small by orders of magnitude. This very mixed list of successes and failures calls into question the early hope that the new particles would provide a proving ground in a simple setting for an underlying theory of hadron dynamics.

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- 8. $\Gamma(\psi' \rightarrow \gamma^3 P_J) \propto (2J+1) p_{\gamma}^3$, assuming they are related electric dipole transitions. Note that we only use the prediction for <u>relative</u> rates for

 $\psi' \rightarrow \gamma^3 P_J$. Because of the heaviness of the quarks and comparatively low gamma ray energies, we are neglecting kinematically possible magnetic quadrupole amplitudes. A more general analysis including such terms can be found, for example, in G. Karl, S. Meshkov and J. Rosner, Phys. Rev., in press.

- 9. The η_c ' has open channels, such as $\gamma \psi$ and possibly $\pi \pi \eta_c$, which are closed to the η_c if it lies below 3.1 GeV.
- 10. Both transitions are magnetic dipole in character, occuring by quark spin flip, with the same spatial wave function initially and finally. If the η_c is X(2.8), then the phase space is much greater for $\psi \rightarrow \gamma \eta_c$.
- 11. This assignment is also not contradicted by other experimental data¹ which is of marginal statistical significance: a few $\pi^+\pi^-$ or K^+K^- events consistent with coming from χ (3545) and the poorly known angular distributions of the gamma ray in $\psi' \rightarrow \gamma \chi$ (3545) and $\psi' \rightarrow \gamma \chi$ (3505).
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- 17. We define all decays of the χ 's other than those into $\gamma \psi$ as being into "hadrons." It should be kept in mind that decays such as $1^+ \rightarrow \pi \pi \eta_c$ may well exist. This should not change our <u>qualitative</u> conclusions on the hadronic decays of the p-wave states, however.
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- 22. These bounds are conservative in that in a non-relativistic picture the overlap integral between the ground state and radially excited wave function contributes four extra powers of p_{γ} to the rate beyond those due to p-wave phase space (see Eichten <u>et al.</u>, Ref. 7). This lowers the bounds by an order of magnitude. Also, if the suppressed decays $\psi' \rightarrow \gamma \eta_c$ and $\eta_c' \rightarrow \gamma \psi$ occur primarily by mixing into the bound state wave functions virtual pairs from the continuum (see Eichten <u>et al.</u>, Ref. 15), this should effect the $\psi' \rightarrow \gamma \eta_c$ decay more (to increase the rate), and the bounds are again conservative.

- 23. Assuming the state at 3505 MeV is the η_c' , and only that the η_c lies below 3.1 GeV, then we find $\Gamma(\eta_c' \rightarrow \text{all}) < 15 \text{ keV}$. For $\chi(3545)$ identified as η_c' , we find similarly that $\Gamma(\eta_c' \rightarrow \text{all}) < 65 \text{ keV}$.
- 24. For example, if $\Gamma(\chi(3455) \rightarrow \text{hadrons})_{\text{direct}} > 3\Gamma(\chi(3455) \rightarrow \gamma \psi)$ and if $\Gamma(\chi(3455) \rightarrow 4\pi^{\pm})/\Gamma(\chi(3455) \rightarrow \text{hadrons})_{\text{direct}} \simeq 0.03$, as expected from other ψ and χ decays, then $\text{BR}(\psi' \rightarrow \gamma\chi(3455) \rightarrow \gamma 4\pi^{\pm}) \gtrsim$ 0.1 $\text{BR}(\psi' \rightarrow \gamma\chi(3455) \rightarrow \gamma\gamma\psi) \gtrsim 10^{-3}$. This is roughly the order of the clearly observed¹ $\text{BR}(\psi' \rightarrow \gamma\chi(3505) \rightarrow \gamma 4\pi^{\pm})$ and $\text{BR}(\psi' \rightarrow \gamma\chi(3545) \rightarrow \gamma 4\pi^{\pm})$.