



# Photoproduction of exotic baryon resonances



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## ABSTRACT

We point out that the new exotic resonances recently reported by LHCb in the  $J/\psi p$  channel are excellent candidates for photoproduction off a proton target. This test is crucial to confirming the resonant nature of such states, as opposed to their being kinematical effects. We specialize to an interpretation of the heavier narrow state as a molecule composed of  $\Sigma_c$  and  $\bar{D}^*$ , and estimate its production cross section using vector dominance. The relevant photon energies and fluxes are well within the capabilities of the GlueX and CLAS12 detectors at Thomas Jefferson National Accelerator Facility (JLAB). A corresponding calculation is also performed for photoproduction of an analogous resonance which is predicted to exist in the  $\Upsilon p$  channel.

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## 1. Introduction

The LHCb experiment [1] has observed two new exotic resonances in the  $J/\psi p$  channel, a broad one with mass  $4380 \pm 8 \pm 29$  MeV, width  $205 \pm 18 \pm 86$  MeV, and statistical significance  $9\sigma$ , and a narrower one with mass  $4449.8 \pm 1.7 \pm 2.5$  MeV, width  $39 \pm 5 \pm 19$  MeV, and statistical significance  $12\sigma$ . In the present note we point out that these states are excellent candidates for photoproduction off a proton target, an observation made by others [2,3] as a preliminary version of this Letter was being prepared. Specializing to an interpretation in which the heavier state is regarded as a molecule of  $\Sigma_c$  and  $\bar{D}^*$  [4], we estimate the cross section for its production using vector dominance. A corresponding calculation is also performed for a molecule of  $\Sigma_b$  and  $B^*$  forming an  $\Upsilon p$  resonance. Observation of the states observed by LHCb in photoproduction is crucial to their confirmation as resonances as opposed to their being kinematic enhancements.

## 2. The reaction $\gamma p \rightarrow X \rightarrow J/\psi p$

We calculate the cross section for photoproduction of a resonance  $X$  decaying to  $J/\psi p$  by assuming it is dominated by the elastic process  $J/\psi p \rightarrow X \rightarrow J/\psi p$ . The photon- $J/\psi$  coupling

is estimated from the  $J/\psi$  leptonic width:  $\Gamma(J/\psi \rightarrow \ell^+ \ell^-) = 5.55 \pm 0.14 \pm 0.02$  keV [5]. The Breit–Wigner cross section for production of a resonance with spin  $J$  by particles of spins  $S_1$  and  $S_2$  is [5]

$$\sigma_{BW}(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k_{in}^2} \frac{B_{in}B_{out}(\Gamma_{tot}^2/4)}{(E-E_R)^2 + (\Gamma_{tot}^2/4)}, \quad (1)$$

where  $k_{in,out}$  are the center-of-mass (CM) 3-momenta in the (incoming  $\gamma p$ , outgoing  $J/\psi p$ ) channel,  $E = E_{cm}$  is the total CM energy,  $E_R$  is the resonance energy,  $B_{in}$  and  $B_{out}$  are the resonance branching fractions into the incoming and outgoing channels, and  $\Gamma_{tot}$  is the resonance total width. For  $E_R = 4380$  MeV,  $k_{in,out}^A = (2090, 741)$  MeV (we use units in which  $c = 1$ ), while for  $E_R = 4450$  MeV,  $k_{in,out}^B = (2126, 820)$  MeV. (We shall denote these resonances  $X_A$  and  $X_B$ , respectively.) In the preferred fits of Ref. [1], one of these resonances has spin  $3/2$ , the other has spin  $5/2$ , and they are of opposite parity. One theoretical interpretation of the narrow higher-lying state as a  $\Sigma_c \bar{D}^*$  molecule bound by pion exchange [4] assigns its spin and parity to be  $J_B^P = 3/2^-$  and therefore  $J_A^P = 5/2^+$ . For an incident photon, with only transverse polarizations, the  $2S_1 + 1$  factor in the denominator is to be multiplied by  $2/3$ .

We define the decay constant  $f_V$  of a vector meson  $V$  in terms of the matrix element between the one- $V$  state and the vacuum:

$$\langle 0 | V_\mu | V(q, \epsilon_\mu) \rangle = \epsilon_\mu M_V f_V, \quad (2)$$

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where  $q$ ,  $\epsilon$ , and  $M_V$  are the four-momentum, polarization vector, and mass of the vector meson. Then dominance of the photoproduction cross section by the  $J/\psi$  pole implies<sup>1</sup>

$$B_{\text{in}}/B_{\text{out}} = (ef_{J/\psi}/M_{J/\psi})^2 f_L (k_{\text{in}}/k_{\text{out}})^{2L+1}, \quad (3)$$

where  $f_L$  is the fraction of decays  $P_c \rightarrow J/\psi p$  in a relative partial wave  $L$  that give rise to a transversely polarized  $J/\psi$ . With our  $J^P$  assignments,  $L = 1, 3$  for  $X_A = P_c(4380)$  and  $L = 0, 2$  for  $X_B = P_c(4450)$ .

The leptonic width of the  $J/\psi$  (neglecting lepton masses) is

$$\Gamma(J/\psi \rightarrow \ell^+ \ell^-) = \frac{4\pi\alpha^2}{3} \frac{f_{J/\psi}^2}{M_{J/\psi}}, \quad (4)$$

from which, using the experimental central value [5], we find

$$f_{J/\psi} = 278 \text{ MeV}, \quad B_{\text{in}}/B_{\text{out}} = 7.37 \times 10^{-4} f_L (k_{\text{in}}/k_{\text{out}})^{2L+1}. \quad (5)$$

For subsequent purposes we shall consider only the photoproduction of the state  $X_B$  decaying to  $J/\psi p$  with relative orbital angular momentum  $L = 0$ , so henceforth  $f_L \equiv f_0$ . It may be easily seen that the cases  $L = 2$  for  $X_B$  and  $L = 1, 3$  for  $X_A$  production lead to higher predicted cross sections, so our estimate may be regarded as a lower bound. The quantity  $f_0$  is given by  $f_0 = 2/(2 + \gamma^2) = 0.651$ , where  $\gamma^2 = 1 + (k_{\text{out}}^B/M_{J/\psi})^2 = 1.070$  accounts for the relativistic enhancement of the longitudinally polarized  $J/\psi$  degree of freedom. This leads to  $B_{\text{in}}/B_{\text{out}} = 1.24 \times 10^{-3}$ . Then the cross section for  $X_B$  production is

$$\sigma_{BW}(E) = \frac{C_B (B_{\text{out}})^2 (k_{\text{in}}^B/k_{\text{in}})^2 (\Gamma_{\text{tot}}^2/4)}{(E - E_R)^2 + (\Gamma_{\text{tot}}^2/4)}, \quad (6)$$

where  $k_{\text{in}} = (E^2 - m_p^2)/(2E)$  is the magnitude of the incoming 3-momentum in the CM. For a photon on a proton target ( $S_2 = 1/2$ ), with  $J_B = 3/2$ , one has

$$C_B \equiv \frac{4\pi}{(k_{\text{in}}^B)^2} \frac{B_{\text{in}}}{B_{\text{out}}}, \quad (7)$$

yielding  $C_B = 1.35 \mu\text{b}$ . This is a substantial cross section, considering that the diffractive cross section for  $\gamma p \rightarrow J/\psi p$  is below 1 nb at  $E = 4.4$  GeV [6–10]. We will return to this subject at the end of the current Section.

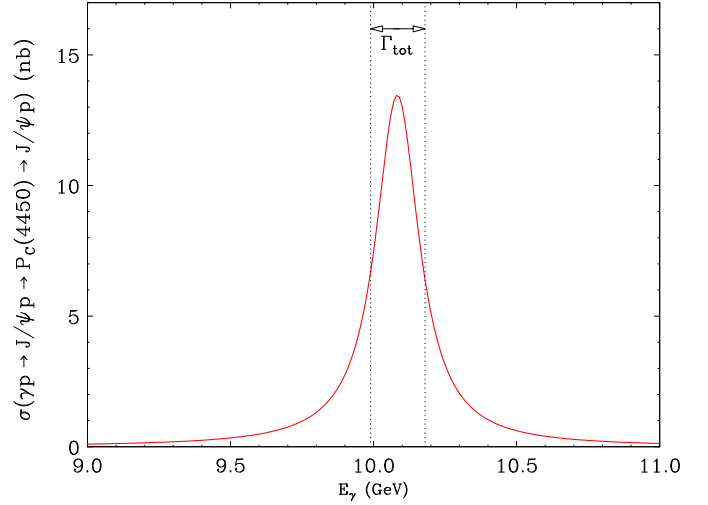
The size of the resonant cross sections is illustrated by Fig. 1 which shows the cross section for case (B), i.e., resonant photoproduction  $\gamma p \rightarrow J/\psi p \rightarrow P_c(4450) \rightarrow J/\psi p$ , as a function of the incident photon laboratory energy  $E_\gamma$ .

The CM energies of 4.38 and 4.45 GeV correspond to laboratory photon energies of 9.75 and 10.08 GeV, respectively, well within the capabilities of the GlueX and CLAS12 detectors at Thomas Jefferson National Accelerator Facility (JLAB) [11,12].

For example, CLAS12 will produce a tagged photon spectrum via bremsstrahlung from an electron beam, yielding a total of  $5 \times 10^7$  photons per second with  $6.5 < E_\gamma < 10.5$  GeV and having a spectrum  $dN_\gamma/dE_\gamma = A/E_\gamma$  [13]. Demanding that the integral of  $dN_\gamma/dE_\gamma$  from 6.5 to 10.5 GeV be  $5 \times 10^7$  photons per second, we find

$$dN_\gamma/dE_\gamma = 1.0 \times 10^8 \text{ photons/s}/E_\gamma. \quad (8)$$

This spectrum may be used to estimate the signal [using Eq. (6)] and background for the resonances  $X_A$  and  $X_B$  with arbitrary spin.



**Fig. 1.** Cross section for resonant photoproduction  $\gamma p \rightarrow J/\psi p \rightarrow P_c(4450) \rightarrow J/\psi p$ , assuming  $B_{\text{out}} = 0.1$ , plotted as function of the incident photon energy  $E_\gamma$ . The vertical dotted lines indicate the width of the  $P_c(4450)$  resonance.

As a sample calculation of the expected number of events we consider here resonant production of  $P_c(4450) \equiv X_B$ . The CM energy range  $m_B - \Gamma_B/2 < E < m_B + \Gamma_B/2$  corresponds to  $9.99 \text{ GeV} < E_\gamma < 10.18 \text{ GeV}$ , i.e.,  $\Delta E_\gamma = 0.19 \text{ GeV}$ . From Eq. (8) we then obtain the number of photons corresponding to  $E$  under the resonance peak:

$$N_\gamma = \int_{9.99 \text{ GeV}}^{10.18 \text{ GeV}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma \approx 2 \times 10^6 \text{ photons/s}. \quad (9)$$

Since the photon beam intensity is given in terms of number of photons per second, rather than in the usual units of luminosity, we shall use here the GlueX rule of thumb that an intensity of  $10^5 \gamma/\text{s}$  will produce about  $10^4$  events per 1  $\mu\text{b}$  of cross section per day of running [11]. So with a peak cross section of  $1.35 (B_{\text{out}})^2 \mu\text{b}$ , a branching fraction  $\mathcal{B}(J/\psi \rightarrow e^+e^-) = (5.971 \pm 0.032)\%$  [5] and the photon flux (9) we should expect  $1.6 \times 10^4 (B_{\text{out}})^2$  events per day of running. While this looks large, we do not know the magnitude of  $B_{\text{out}}$ .

In the region of interest the  $E_\gamma$  resolution is 20–30 MeV, corresponding to 4–6 MeV resolution in  $E$ . This is much less than the 39 MeV width (in  $E$ ) of the  $P_c(4450)$  resonance, so it should be possible to resolve the peak in Fig. 1. It is likely that in the future the  $E_\gamma$  resolution will be even better [13]. For details of a specific CLAS12 proposal to study  $J/\psi$  production with a tagged polarized photon beam of energy 11 GeV, see Ref. [14]. Such a beam enables useful measurements of resonance spin-parity via angular distributions of the final  $e^+e^-$  pair in  $J/\psi$  decay [15].

In the future the GlueX detector [11,16] will complement the reach of CLAS12. A specific proposal to study  $\gamma p \rightarrow J/\psi p$  with  $8.7 < E_\gamma < 11.5$  GeV [17], optimized for a peak in the photon spectrum at 10 GeV [18], leads one to expect about  $6 \times 10^{-4}$  events/MeV/s/ $\mu\text{b}$  (with  $J/\psi \rightarrow e^+e^-$ ). Integration with respect to CM energy  $E$  over a Breit-Wigner resonance with maximum  $\sigma_{\text{peak}}$  and width  $\Gamma$  multiplies  $\sigma_{\text{peak}}$  by a factor of  $\pi\Gamma/2 = 61.26 \text{ MeV}$ . But we want to integrate with respect to laboratory photon energy  $E_\gamma$ , so we have to multiply by  $dE_\gamma/dE = E/m_p = 4.743$ , giving a factor of 290.5 MeV. Multiplying by  $\sigma_{\text{peak}} = 1.35 \mu\text{b} (B_{\text{out}})^2$  one estimates a rate of about  $2 \times 10^4 (B_{\text{out}})^2$  events of the 4450 MeV state per day, roughly consistent with our estimate for CLAS12. As for energy resolution, GlueX expects a RMS tagged photon uncertainty around 6 MeV. On a proton target, this

<sup>1</sup> We thank M. Voloshin for a correction to a preliminary version of this Letter.

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