EXOTIC BARYON RESONANCES IN PHOTOPRODUCTION

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Dedicated to Andrzej Bialas in honour of his 80th birthday

The new exotic pentaquark resonances recently reported by LHCb in the $J/\psi\, p$ channel are excellent candidates for photoproduction off a proton target. Such photoproduction experiments are a crucial test for confirming that these states are genuine resonances rather than a kinematical artifact. We focus on the interpretation of the heavier narrow state as a deuteron-like bound state of Σ_c and $\bar{D}^*$, and employ vector dominance to estimate its production cross section. The relevant experiments can likely be performed in GlueX and CLAS12 detectors at JLAB which have the relevant photon energies and fluxes. We also perform a calculation for photoproduction of an analogous resonance in the bottomonium sector, predicted to exist in the Υp 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 9σ, 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 12σ. For a recent review, see [2].

In the present note, we point out that these states are excellent candidates for photoproduction off a proton target, an observation made by others [3, 4] 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 Σ_c and $\bar{D}^*$ [5], we estimate the cross section for its production using vector dominance. A corresponding calculation is also performed for a molecule of Σ_b and B^* forming an Υp resonance. Observation of the states made by LHCb in photoproduction is crucial to their confirmation as resonances, as opposed to their being kinematic enhancements.

2. The reaction $\gamma\, p \to X \to J/\psi\, p$

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 $J/\psi\, p \to X \to J/\psi\, p$. The photon–$J/\psi$ coupling is estimated from the J/ψ leptonic width: $\Gamma(J/\psi \to \ell^+\ell^-) = 5.55 \pm 0.14 \pm 0.02$ keV [6]. The Breit–Wigner cross section for production of a resonance with spin J by particles of spins S_1 and S_2 is [6]

$$\sigma_{\rm BW}(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)}\,\frac{4\pi}{k_{\rm in}^2}\,\frac{B_{\rm in}B_{\rm out}\left(\Gamma_{\rm tot}^2/4\right)}{(E-E_{\rm R})^2+\left(\Gamma_{\rm tot}^2/4\right)}\,, \tag{1}$$

where $k_{\rm in,out}$ are the center-of-mass (CM) 3-momenta in the (incoming γp, outgoing $J/\psi\, p$) channel, $E = E_{\rm cm}$ is the total CM energy, $E_{\rm R}$ is the resonance energy, $B_{\rm in}$ and $B_{\rm out}$ are the resonance branching fractions into the incoming and outgoing channels, and $\Gamma_{\rm tot}$ is the resonance total width. For $E_{\rm R} = 4380$ MeV, $k^A_{\rm in,out} = (2090, 741)$ MeV (we use units in which $c = 1$), while for $E_{\rm R} = 4450$ MeV, $k^B_{\rm in,out} = (2126, 820)$ 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 [5] assigns its spin and parity to be $J^P_B = 3/2^-$ and, therefore, $J^P_A = 5/2^+$. 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

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

where q, ϵ, 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/ψ pole implies[1]

$$B_{\rm in}/B_{\rm out} = \left(e f_{J/\psi}/M_{J/\psi}\right)^2 f_L\,(k_{\rm in}/k_{\rm out})^{\,2L+1}\,, \tag{3}$$

[1] We thank M. Voloshin for a correction to a preliminary version of this Letter.

where f_L is the fraction of decays $P_c \to J/\psi\, p$ in a relative partial wave L that give rise to a transversely polarized J/ψ. 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/ψ (neglecting lepton masses) is

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

from which, using the experimental central value [6], we find

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

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 $\gamma^2 = 1 + (k_{\mathrm{out}}^B/M_{J/\psi})^2 = 1.070$ accounts for the relativistic enhancement of the longitudinally polarized J/ψ degree of freedom. This leads to $B_{\mathrm{in}}/B_{\mathrm{out}} = 1.24 \times 10^{-3}$. Then, the cross section for X_B production is

$$\sigma_{\mathrm{BW}}(E) = \frac{C_B (B_{\mathrm{out}})^2 \left(k_{\mathrm{in}}^B/k_{\mathrm{in}}\right)^2 \left(\Gamma_{\mathrm{tot}}^2/4\right)}{(E - E_{\mathrm{R}})^2 + \left(\Gamma_{\mathrm{tot}}^2/4\right)}\,, \tag{6}$$

where $k_{\mathrm{in}} = (E^2 - m_p^2)/(2E)$ 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

$$C_B \equiv \frac{4\pi}{\left(k_{\mathrm{in}}^B\right)^2}\,\frac{B_{\mathrm{in}}}{B_{\mathrm{out}}}\,, \tag{7}$$

yielding $C_B = 1.35\ \mu\mathrm{b}$. This is a substantial cross section, considering that the diffractive cross section for $\gamma p \to J/\psi\, p$ is below 1 nb at $E = 4.4$ GeV [7–11]. 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 the case (B), *i.e.*, resonant photoproduction $\gamma p \to J/\psi\, p \to P_c(4450) \to J/\psi\, p$, as a function of the incident photon laboratory energy E_γ.

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 the Thomas Jefferson National Accelerator Facility (JLAB) [12, 13].

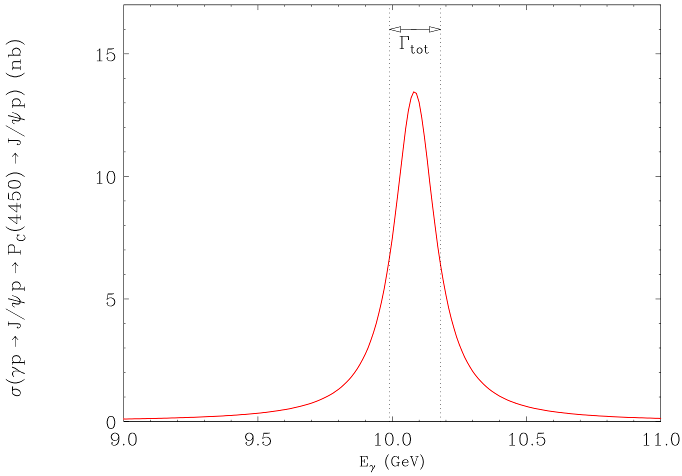

Fig. 1. $\sigma(\gamma p \to J/\psi\, p \to P_c(4450) \to J/\psi\, p)$ resonant photoproduction cross section *vs.* the incident photon energy E_γ, assuming $B_{\rm out} = 0.1$ (see the text). The width of the $P_c(4450)$ resonance is indicated by the vertical dotted lines.

For example, CLAS12 will produce a tagged photon spectrum via bremsstrahlung from an electron beam, yielding a total of 5×10^7 photons per second with $6.5 < E_\gamma < 10.5$ GeV and having a spectrum $\mathrm{d}N/\mathrm{d}E_\gamma = A/E_\gamma$ [14]. Demanding that the integral of $\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$ from 6.5 to 10.5 GeV be 5×10^7 photons per second, we find

$$\mathrm{d}N_\gamma/\mathrm{d}E_\gamma = 1.0 \times 10^8 \ \text{photons/s}/E_\gamma\,. \tag{8}$$

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

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 GeV $< E_\gamma <$ 10.18 GeV, *i.e.*, $\Delta E_\gamma = 0.19$ GeV. From Eq. (8), we then obtain the number of photons corresponding to E under the resonance peak

$$N_\gamma = \int\limits_{9.99\,\text{GeV}}^{10.18\,\text{GeV}} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma \approx 2 \times 10^6 \ \text{photons/s}\,. \tag{9}$$

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 γ/s will produce about 10^4 events per 1 μb of cross section per day of running [12]. So with a peak cross section of 1.35 $(B_{\rm out})^2\mu$b, a branching fraction $\mathcal{B}(J/\psi \to e^+e^-) = (5.971 \pm 0.032)\%$ [6] and the photon flux (9), we should expect $1.6\times 10^4\ (B_{\rm out})^2$ events per day of running. While this looks large, we do not know the magnitude of $B_{\rm out}$.

In the region of interest, the E_γ 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_γ resolution will be even better [14]. For details of a specific CLAS12 proposal to study J/ψ production with a tagged polarized photon beam of energy 11 GeV, see Ref. [15]. Such a beam enables useful measurements of resonance spin-parity via angular distributions of the final e^+e^- pair in J/ψ decay [16].

In the future, the GlueX detector [12, 17] will complement the reach of CLAS12. A specific proposal to study $\gamma p \to J/\psi\, p$ with $8.7 < E_\gamma < 11.5$ GeV [18], optimized for a peak in the photon spectrum at 10 GeV [19], leads one to expect about 6×10^{-4} events/MeV/s/μb (with $J/\psi \to e^+e^-$). Integration with respect to CM energy E over a Breit–Wigner resonance with maximum $\sigma_{\rm peak}$ and width Γ multiplies $\sigma_{\rm peak}$ by a factor of $\pi\Gamma/2 = 61.26$ MeV. But we want to integrate with respect to laboratory photon energy E_γ, so we have to multiply by $\mathrm{d}E_\gamma/\mathrm{d}E = E/m_p = 4.743$, giving a factor of 290.5 MeV. Multiplying by $\sigma_{\rm peak} = 1.35\ \mu{\rm b}(B_{\rm out})^2$, one estimates a rate of about $2 \times 10^4 (B_{\rm out})^2$ events of the 4450 MeV state per day, roughly consistent with our estimate for CLAS12. As for energy resolution, GlueX expects a r.m.s. tagged photon uncertainty around 6 MeV. On a proton target, this translates into an uncertainty in E of 1 MeV for a 10 GeV photon [17], which should enable an accurate scan of the resonance lineshape.

The branching fraction $B_{\rm out}$ cannot be too small, as the $P_c(4450) \to J/\psi\, p$ signal is 4.1% of the $J/\psi\, p$ final state in $\Lambda_b \to K^- J/\psi\, p$ [1]. If $B_{\rm out}$ is too small, the value of $\mathcal{B}(\Lambda_b \to K^- P_c)$, with P_c decaying to final states other than $J/\psi\, p$, becomes unreasonably large in comparison with $\mathcal{B}(\Lambda_b \to K^- J/\psi\, p) = 3 \times 10^{-4}$ [16].

2.0.1. Comparison with J/ψ photoproduction data near threshold

The elastic J/ψ photoproduction cross section for $10 < E_\gamma < 13$ GeV has been measured by SLAC and Cornell teams in 1975 and is quite small, below 1 nb [7–11]. This raises an obvious question: Why was not the $P_c(4450)$ resonance observed by these experiments? There are several effects, all working in the same direction, as listed below.

(a) Smearing by poor energy resolution: The $P_c(4450)$ width is quite small, 39 MeV, corresponding to 180 MeV in terms of the photon energy. The photon energy in the early experiments had a rather large spread. For example, in the Cornell study [8], the photon energy was divided into three intervals: 9.3–10.4, 10.4–11.1, 11.1–11.8 GeV. The narrow peak is smeared out when convoluted with such a wide energy distribution.

(b) Mostly forward scattering: Experiments [7, 8] focused on the forward cross section, which is mostly due to diffractive scattering, while resonance scattering tends to be much more isotropic. Therefore, only a small fraction of the resonant cross section is in the forward direction.

(c) $B_{\rm out} \ll 1$: The branching fraction of the resonance into $J/\psi\, p$ might be significantly less than 1. In this context, it is interesting to point out that Ref. [7] used vector dominance to derive the estimate

$$\left.\frac{{\rm d}\sigma(\gamma p \to J/\psi\, p)}{{\rm d}t}\right|_{t=0} \simeq 25\ \mu{\rm b/GeV}^2\,. \qquad (10)$$

Assuming that the forward $J/\psi\, p$ scattering amplitude is purely imaginary, they then used the optical theorem to derive the bound $\sigma_{\rm tot}(J/\psi\, p) \leq 0.8$ mb.

3. The reaction $\gamma p \to X \to \Upsilon p$

It was suggested in Ref. [5] that an exotic doubly-heavy meson or baryon resonance should exist near any threshold if pion exchange is allowed between the two constituent hadrons. In particular, there should exist a relatively narrow $J^P = 3/2^-$ resonance near $\Sigma_b B^*$ threshold, or 11.14 GeV, decaying to $\Upsilon(nS)p$. We shall estimate the cross section for photoproduction of such a resonance, denoted by $P_b(11140)$. The corresponding photon energy in the laboratory is $E_\gamma = 65.66$ GeV. In principle, such an energy could be achieved using tagged photons from HERA.

The calculation for resonant $\Upsilon(1S)\, p$ photoproduction is entirely analogous to the one for J/ψ. Using the experimental value [6] $\Gamma(\Upsilon(1S) \to e^+e^-) = 1.34$ keV, we obtain

$$f_{\Upsilon(1S)} = 238\ {\rm MeV}\,. \qquad (11)$$

We then find, for a $\Upsilon(1S)\, p$ resonance of mass $E_{\rm R} = 11.14$ GeV, with $k^{\rm R}_{\rm in,out} = (5.530, 1.287)$ GeV the (incoming, outgoing) CM 3-momentum for $E = E_{\rm R}$,

$$\begin{aligned} B_{\rm in}/B_{\rm out} &= \left(ef_\Upsilon/M_\Upsilon\right)^2 f_0\,(k_{\rm in}/k_{\rm out}) \\ &= \left(5.82\times10^{-5}\right)(0.663)(4.30) = 1.66\times10^{-4}\,. \end{aligned} \qquad (12)$$

The photoproduction cross section for such a resonance with width $\Gamma_{\rm tot}$ is given by

$$\sigma_{\rm BW}(E) = \frac{C_{\rm R}(B_{\rm out})^2\left(k^{\rm R}_{\rm in}/k_{\rm in}\right)^2\left(\Gamma^2_{\rm tot}/4\right)}{(E-E_{\rm R})^2+\left(\Gamma^2_{\rm tot}/4\right)} \qquad (13)$$

where, for $J = 3/2$,

$$C_{\rm R} \equiv \frac{4\pi}{\left(k_{\rm in}^{\rm R}\right)^2}\,\frac{B_{\rm in}}{B_{\rm out}} = 26.6\ {\rm nb}\,. \tag{14}$$

The cross section for resonant photoproduction $\gamma p \to \Upsilon(1S)p \to P_b(11140) \to \Upsilon(1S)p$ is shown in Fig. 2 as a function of the incident photon energy E_γ. Here, we have assumed the same width as $P_c(4450)$, *i.e.*, $\Gamma = 39$ MeV. The actual width is likely to be narrow, but its precise value is unknown. It is given by the product of the square of the matrix element and the phase space. Under the assumption that $B_{\rm out}$ is close to 1, the phase space scales as $k_{\rm out}^{\rm R}$ for an S-wave decay. If the matrix element remained unchanged, it would yield $\Gamma(P_b) = \Gamma(P_c)(k_{\rm out}^{P_b}/k_{\rm out}^{P_c}) = 61$ MeV. The matrix element is given by the overlap of the $\Upsilon\,p$ and $\Sigma_b B^*$ molecule wave functions. This overlap is likely to be less than the overlap of that between the $J/\psi\,p$ and $\Sigma_c\bar{D}^*$ wave functions as a result of the more compact nature of the Υ, but we do not have a quantitative estimate. In the more likely case that $B_{\rm out}$ is much less than 1, $\Gamma(P_b)$ will depend on details of the molecular binding of Σ_b and B^*.

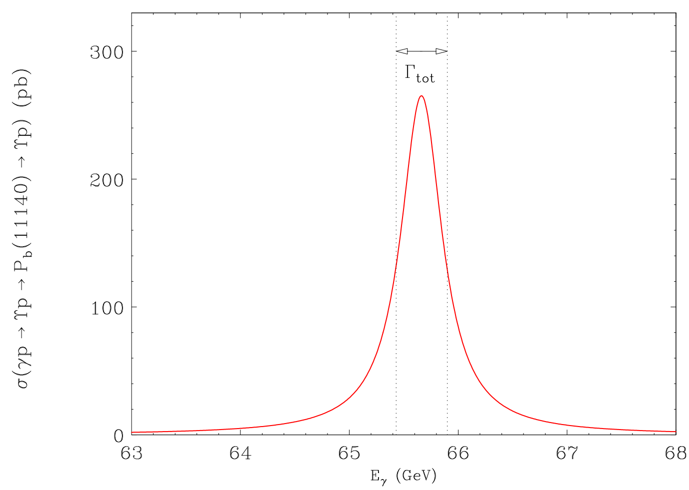

Fig. 2. $\sigma(\gamma p \to \Upsilon(1S)p \to P_b(11140) \to \Upsilon(1S)p)$ resonant photoproduction cross section *vs.* the incident photon energy E_γ, assuming $B_{\rm out} = 0.1$ (see the text). The width of the $P_b(11140)$ resonance is indicated by the vertical dotted lines.

The corresponding background is the diffractive process $\gamma p \to \Upsilon(nS)p$. A few events of $\gamma p \to \Upsilon(1S)p$ were seen in 1995–1997 data by the ZEUS Collaboration at HERA [20]. They quoted a ratio

$$\sigma_{\rm el}(\gamma p \to \Upsilon(1S)p)/\sigma_{\rm el}(\gamma p \to J/\psi\,p) \sim 5\times 10^{-3}\,. \tag{15}$$

At 11 GeV, Ref. [11] estimated $\sigma_{\rm el}(\gamma p \to J/\psi\, p) \simeq 10$ nb, yielding $\sigma_{\rm el}(\gamma p \to \Upsilon p) \simeq 50$ pb. In later ZEUS data with $62 \pm 12\ \Upsilon(1S)$ events [21], $\sigma(\gamma p \to \Upsilon p)$ was measured in various ranges of center-of-mass energy W to be

$$\begin{array}{lll} 160 \pm 51^{+48}_{-21}\ \text{pb}\,, & 60 < W < 130\ \text{GeV}\,, & \text{Central}\ W_0 = 100\ \text{GeV}\,, \\ 321 \pm 88^{+46}_{-114}\ \text{pb}\,, & 130 < W < 220\ \text{GeV}\,, & \text{Central}\ W_0 = 180\ \text{GeV}\,. \\ 235 \pm 47^{+30}_{-40}\ \text{pb}\,, & 60 < W < 220\ \text{GeV}\,, & \end{array}$$

Comparing cross sections at $W_0 = 100$ and 180 GeV, they scale as $W^{1.18}$. Assuming this dependence to extrapolate to 11 GeV gives a cross section of 12 pb at that energy.

4. Conclusions

The narrow resonance of mass 4450 MeV and a broader enhancement at 4380 MeV, discovered by LHCb through their decay to $J/\psi\, p$, provide the first robust experimental evidence for existence of exotic baryons containing five quarks — $\{uud\bar{c}c\}$. It is essential to confirm the LHCb results by searching for these states in a different experimental setup. We suggest their photoproduction on proton targets using photons with energy $\sim$10 GeV. We predict cross sections that are substantially above the diffractive $\gamma p \to J/\psi\, p$ background. An analogous state in the bottomonium sector, close to the $\Sigma_b B^*$ threshold, is predicted [5] near 11.14 GeV and should be photoproduced with photons of energy near 66 GeV. The observation of signals in the $\gamma p \to J/\psi\, p$ channel would provide important confirmation of the resonant nature of the LHCb states. The observation of a narrow resonance in the $\gamma p \to \Upsilon p$ channel would be a major new discovery and would strongly indicate existence of many further resonances of hadronic molecule type, as advocated in Ref. [5].

This paper is based on joint work with Jon Rosner [22].

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