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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 Σ_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 Υp channel.

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. 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 Σ_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 Σ_b and B^* forming an Υp 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 $\gamma\, p \to X \to J/\psi\, p$

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 [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]

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

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_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 $E_R = 4380$ MeV, $k^A_{\rm in,out} = (2090, 741)$ MeV (we use units in which $c = 1$), while for $E_R = 4450$ 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 [4] 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:

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

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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]

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

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

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

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

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

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

$$\sigma_{BW}(E) = \frac{C_B (B_{\rm out})^2 (k^B_{\rm in}/k_{\rm in})^2 (\Gamma^2_{\rm tot}/4)}{(E - E_R)^2 + (\Gamma^2_{\rm tot}/4)} , \quad (6)$$

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

$$C_B \equiv \frac{4\pi}{(k^B_{\rm in})^2}\,\frac{B_{\rm in}}{B_{\rm out}} , \quad (7)$$

yielding $C_B = 1.35$ μb. 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 [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 $\gamma p \to J/\psi\, p \to P_c(4450) \to J/\psi\, p$, 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 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 5×10^7 photons per second with $6.5 < E_\gamma < 10.5$ GeV and having a spectrum $dN/dE_\gamma = A/E_\gamma$ [13]. Demanding that the integral of dN_γ/dE_γ from 6.5 to 10.5 GeV be 5×10^7 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.

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

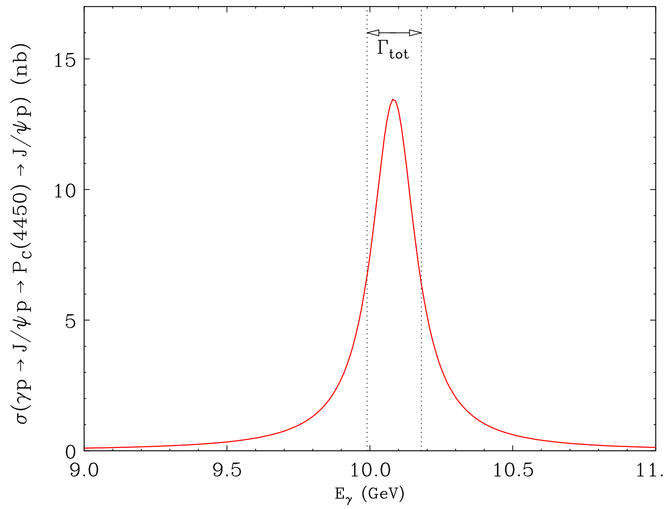

Fig. 1. Cross section for resonant photoproduction $\gamma p \to J/\psi\, p \to P_c(4450) \to J/\psi\, p$, assuming $B_{\rm out} = 0.1$, plotted as function of the incident photon energy E_γ. The vertical dotted lines indicate the width of the $P_c(4450)$ resonance.

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 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:

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

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 γ/s will produce about 10^4 events per 1 μb of cross section per day of running [11]. So with a peak cross section of 1.35 $(B_{\rm out})^2$ μb, a branching fraction $\mathcal{B}(J/\psi \to e^+e^-) = (5.971 \pm 0.032)\%$ [5] 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 [13]. For details of a specific CLAS12 proposal to study J/ψ 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/ψ decay [15].

In the future the GlueX detector [11,16] 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 [17], optimized for a peak in the photon spectrum at 10 GeV [18], 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 $dE_\gamma/dE = E/m_p = 4.743$, giving a factor of 290.5 MeV. Multiplying by $\sigma_{\rm peak} =$ 1.35 μb$(B_{\rm out})^2$ 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 RMS 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 [16], which should enable an accurate scan of the resonance lineshape.

The branching fraction B_{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_{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 $\mathcal{B}(\Lambda_b \to K^- J/\psi\ p) = 3 \times 10^{-4}$ [15].

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 [6–10]. This raises an obvious question: Why wasn't 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 photon energy. The photon energy in the early experiments had a rather large spread. For example, in the Cornell study [7] 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 [6,7] 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) $B_{out} \ll 1$: 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. [6] used vector dominance to derive the estimate

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

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

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

It was suggested in Ref. [4] 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 [5] $\Gamma(\Upsilon(1S) \to e^+e^-) = 1.34$ keV, we obtain

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

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

$$\begin{aligned} B_{in}/B_{out} &= (ef_\Upsilon/M_\Upsilon)^2 f_0(k_{in}/k_{out}) \\ &= (5.82 \times 10^{-5})(0.663)(4.30) = 1.66 \times 10^{-4}\,. \end{aligned} \qquad (12)$$

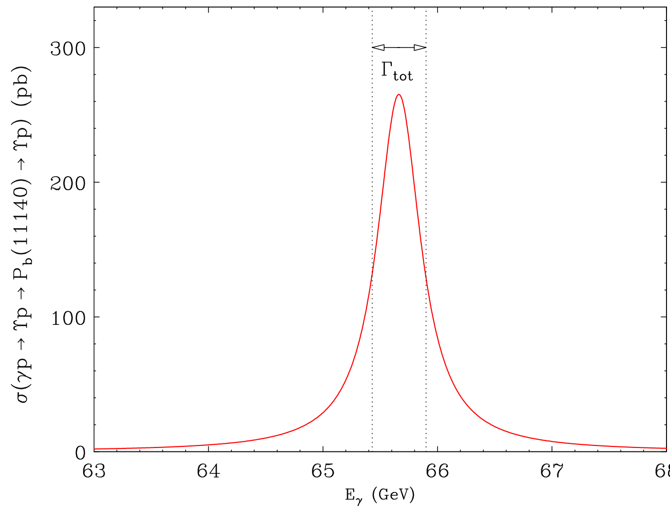

Fig. 2. Cross section for resonant photoproduction $\gamma p \to \Upsilon(1S)p \to P_b(11140) \to \Upsilon(1S)p$ assuming $B_{out} = 0.1$, plotted as function of the incident photon energy E_γ. The vertical dotted lines indicate the width of the $P_b(11140)$ resonance.

The photoproduction cross section for such a resonance with width Γ_{tot} is given by

$$\sigma_{BW}(E) = \frac{C_R(B_{out})^2(k^R_{in}/k_{in})^2(\Gamma^2_{tot}/4)}{(E-E_R)^2 + (\Gamma^2_{tot}/4)}\,, \qquad (13)$$

where, for $J = 3/2$,

$$C_R \equiv \frac{4\pi}{(k^R_{in})^2}\,\frac{B_{in}}{B_{out}} = 26.6\ \text{nb}\,. \qquad (14)$$

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_{out} is close to 1, the phase space scales as k^R_{out} for an S-wave decay. If the matrix element remained unchanged, it would yield $\Gamma(P_b) = \Gamma(P_c)(k^{P_b}_{out}/k^{P_c}_{out}) = 61$ 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_{out} is much less than 1, $\Gamma(P_b)$ will depend on details of the molecular binding of Σ_b and B^*.

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 1995–7 data by the ZEUS Collaboration at HERA [19]. They quoted a ratio

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

At 11 GeV, Ref. [10] estimated $\sigma_{el}(\gamma p \to J/\psi\ p) \simeq 10$ nb, yielding $\sigma_{el}(\gamma p \to \Upsilon p) \simeq 50$ pb. In later ZEUS data with 62 ± 12 $\Upsilon(1S)$ events [20], $\sigma(\gamma p \to \Upsilon p)$ was measured in various ranges of center-of-mass energy W to be

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

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 discovery in the LHCb experiment of a narrow resonance of mass 4450 MeV and a broader enhancement at 4380 MeV, both of which decay to $J/\psi\, p$, suggests that one search for photoproduction of these states on proton targets using photons of energy near 10 GeV. Predicted cross sections are at an encouraging level above diffractive $\gamma p \to J/\psi\, p$ background. On the basis of proximity to the $\Sigma_b B^*$ threshold, a predicted state [4] near 11.14 GeV should be photoproduced with photons of energy ~ 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 yet additional resonances, along the lines advocated in Ref. [4].

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