J/ψ N photoproduction on deuterium as a test for exotic baryons

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ABSTRACT

We extend a previous study of photoproduction of exotic baryon resonances to the reaction γ + d → J/ψ + n + p, which permits simultaneous investigation of the reactions γ + p → P_{c}^{+} → J/ψ p (n spectator) and γ + n → P_{c}^{0} → J/ψ n (p spectator). Here P_{c}^{+} is an exotic baryon with quark content c̄cuud, and P_{c}^{0} is its hypothetical isospin partner with quark content c̄cddu. We find: (1) The cross section for J/ψ n photoproduction should be equal to that for J/ψ p photoproduction if these processes are dominated by the photon coupling to a c̄c pair. In that case the two processes are equal by isospin reflection. (2) If a P_{c}^{+} candidate is a genuine c̄cuud resonance, its isospin partner P_{c}^{0} = c̄cdu should have the same mass (again by isospin reflection). (3) In the absence of Fermi motion, the cross section for photoproduction of P_{c} off a deuteron should be nearly the sum of two equal cross sections: σ(γp → P_{c}^{+}) (spectator n) and σ(γn → P_{c}^{0}) (spectator p). (4) The effects of Fermi motion are significant. They include smearing, form-factor suppression and offshellness. The upshot is that the resonance is significantly wider and the peak cross section off a deuteron is expected to be considerably less than twice that in γp.

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Two candidates for baryon resonances composed of four quarks and an antiquark have been reported by the LHCb Collaboration [1], challenging the conventional picture of baryons as exclusively three-quark states. The new states are a broad one with mass 4380 ± 8 ± 29 MeV, width 205 ± 18 ± 86 MeV, and statistical significance 9σ, and a narrower one with mass 4449.8 ± 1.7 ± 2.5 MeV, width 39 ± 5 ± 19 MeV, and statistical significance 12σ. They are seen decaying into J/ψ p, suggesting that their quark content is

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The proximity of the narrow higher-mass state to the \( \Sigma_c \bar{D}^* \) threshold led to its interpretation \cite{2} as an \( S \)-wave \( \Sigma_c \bar{D}^* \) molecule, while no convincing molecular interpretation was found for the broad lower-mass state.

In order to establish either or both \( P_c^+(4380) \) and \( P_c^+(4450) \) as genuine resonances rather than kinematic enhancements, one must observe them in reactions other than the discovery channel \( \Lambda_b \rightarrow K^- J/\psi p \). Several authors \cite{3,4,5} proposed the photoproduction direct-channel reaction \( \gamma p \rightarrow P_c^+ \rightarrow J/\psi p \), for which beams at the Thomas Jefferson National Accelerator Facility (JLAB) are uniquely suited. In the present note we extend our proposal to photoproduction off deuterium. We find:

1. The cross section for \( J/\psi n \) photoproduction should be equal to that for \( J/\psi p \) photoproduction if these processes are dominated by the photon coupling to a \( c \bar{c} \) pair. In that case the two processes are equal by isospin reflection.

2. If a \( P_c^+ \) candidate is a genuine \( c\bar{c}uud \) resonance, its isospin partner \( P_c^0 = c\bar{c}ddu \) should have the same mass (again by isospin reflection).

3. In the absence of Fermi motion, the cross section for photoproduction of \( P_c \) off a deuteron should be nearly the sum of two equal cross sections: \( \sigma(\gamma p \rightarrow P_c^+) \) (spectator \( n \)) and \( \sigma(\gamma n \rightarrow P_c^0) \) (spectator \( p \)).

4. The effects of Fermi motion are significant. They include smearing, form-factor suppression and offshellness. The upshot is that the cross section off a deuteron is expected to be larger than, but less than twice that in \( \gamma p \).

We now give details. An Appendix contains material relevant to the use of a deuteron target.

It is difficult to create a heavy \( c\bar{c} \) pair in a hadronic reaction, whereas electromagnetic production of \( c\bar{c} \) (as in electron-positron annihilation) is governed only by the \( c \)-quark electric charge. We are thus justified in assuming that the reaction \( \gamma + p \rightarrow X^+ \rightarrow J/\psi + p \) mainly involves the coupling of the photon to a \( c\bar{c} \) pair, and thus the resonance \( X^+ \) has isospin \( I = 1/2 \) and third isospin component \( I_3 = +1/2 \).

Then invariance of the strong interactions under isospin reflection implies

\[
\sigma(\gamma + p \rightarrow X^+ \rightarrow J/\psi + p) = \sigma(\gamma + n \rightarrow X^0 \rightarrow J/\psi + n),
\]

where \( X^0 \) with \( I = 1/2, I_3 = -1/2 \) is the isospin partner of \( X^+ \).

Suppose the \( J/\psi p \) system has a resonance \( P_c^+ \). (The LHCb data suggest two such states.) Then since the isospin of \( J/\psi \) is zero, a corresponding resonance \( P_c^0 \) should show up in the \( J/\psi n \) channel. We can see that this general conclusion is valid also in the specialized case of a molecule. In that case \( P_c^+(4450) \) will be composed of \( \Sigma_c^{++} \bar{D}^{*-} \) with weight 2/3 and \( \Sigma_c^+ \bar{D}^{*0} \) with weight 1/3, taking account of isospin Clebsch-Gordan coefficients. The isospin-reflected state will be \( P_c^0(4450) \), composed of \( \Sigma_c^0 \bar{D}^{*0} \) with weight 2/3 and \( \Sigma_c^+ \bar{D}^{*-} \) with weight 1/3.

Consider now the photoproduction of \( J/\psi \) on a deuterium target. The shallow binding energy of the deuteron (2.2 MeV) implies that its constituents are nearly free, with typical momenta only of order 50 MeV but with a long tail (see Appendix). This seemingly small amount, however, is enough to cause considerable spread (of order 5%) in the incident photon energy needed to excite a narrow resonance at 4450 MeV.

To get a feeling for the size of the effect, consider first photoproduction with real photons off a static neutron target. To excite a resonance at 4449.8 MeV, the required incident photon energy is 10,068 MeV. If instead the momentum of the target neutron is 50 MeV...
parallel to the photon beam, the required photon energy goes up to 10,618 MeV. For 50 MeV anti-parallel momentum, it goes down to 9546 MeV.

In Fig. 1 of Ref. [5], the effective width of a $P_c(4450)$ photoproduced on a stationary proton target was estimated to be 0.19 GeV. By contrast, accounting for Fermi momentum in the deuteron gives rise to an excitation curve with effective width of about 0.9 GeV, as shown in Fig. 1. This leads to a degradation by nearly a factor of five of the peak resonant cross section estimated in Ref. [5].

In principle, detection of a recoil nucleon $N = p, n$ in the reaction $\gamma + d \rightarrow P_c(4450) + N$ would provide a kinematic constraint reducing the needed photon energy spread. However, as the average recoil momentum is less than 100 MeV/c, one does not expect current detectors to be capable of this.

Two additional effects that might reduce the expected cross-section as result of the Fermi motion are (a) suppression due to strong dependence of the form factor on $s = E_{CM}^2$ and (b) suppression due to the target nucleon being offshell.

(a) In exclusive processes the cross section falls off quickly like a high power of $1/E_{CM}$, given by the “quark counting rules” [7]. It is therefore affected by Fermi motion. In particular, the non-resonant cross-section will be higher if the neutron is moving in the direction of the photon beam, because CM energy is lower then.
The kinetic energy of an onshell nucleon with momentum 100 MeV is about 5.3 MeV. A nucleon bound inside a deuteron with nonzero Fermi momentum must therefore be somewhat offshell, to maintain the total mass of the deuteron unchanged. The $\gamma N$ cross-section for offshell nucleon may be somewhat lower than for onshell nucleon.

To conclude, the photoproduction of $P_c(4450)$ on a deuteron target would allow an important check of its nature as a genuine resonance with isospin 1/2. Because of kinematic smearing due to the deuteron wave function, the identification of this state is somewhat more challenging than in its photoproduction on a hydrogen target.

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Appendix: Effects of deuteron wave function

We use parameters of an S-wave Hulthén wave function quoted in Ref. [8]:

$$\psi(\vec{r}) = (c/r)[e^{-\alpha r} - e^{-\beta r}],$$

where $\alpha = 0.232$ fm$^{-1}$, $\beta = 1.202$ fm$^{-1}$, and $c = 0.2601$ ensures the normalization of the wave function. This form is easily Fourier-transformed, with the result (leaving only the dependence on the magnitude of momentum)

$$\psi(k) = 4\pi c \left[ \frac{\beta^2 - \alpha^2}{(\alpha^2 + k^2)(\beta^2 + k^2)} \right],$$

as shown in Fig. 2 (left). The normalization of $|\psi(k)|^2$ when integrated over $4\pi k^2dk/(2\pi)^3$ is 1. Equivalently, in cylindrical coordinates,

$$2\pi \int k_\perp dk_\perp dk_z |\psi(k)|^2/(2\pi)^3 = 1,$$

where $k^2 = k_{\perp}^2 + k_z^2$. In order to calculate the smearing in incident photon energy needed to excite a state at fixed CM energy, we need the distribution in longitudinal momentum $k_z$. Performing just the $k_\perp$ integral in (4), we find

$$\frac{dN}{dk_z} = 2e^2 \left[ \frac{1}{\alpha^2 + k_z^2} + \frac{1}{\beta^2 + k_z^2} + \frac{2}{(\beta^2 - \alpha^2)} \log \frac{\alpha^2 + k_z^2}{\beta^2 + k_z^2} \right],$$

as shown in Fig. 2 (right).

The relation between incident photon energy and $k_z$ may be written in simplified form as

$$E_\gamma \simeq \frac{E_{\text{CM}}^2 - m_N^2}{2(m_N - k_z)},$$

where we have neglected a small correction due to the recoil nucleon’s kinetic energy. This allows one to transform the distribution in Fig. 2 (left) into that shown in Fig. 1.
Figure 2: Left: Momentum-space distribution of nucleons inside a deuteron as given by Eq. (3). The normalization is such that the integral over $k$ is 1. The peak at $k \approx 0.22 \text{ fm}^{-1}$ corresponds to a momentum of 43 MeV/c. Right: Longitudinal momentum distribution of a nucleon in a deuteron, as given by Eq. (5). The normalization is such that the integral over $k_z$ is 1.

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