Plausibility of the LHCb $P_c(4312)^+$ in the GlueX $\gamma p \to J/\psi p$ total cross sections

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New high-statistics total cross-section data for $\gamma p \to J/\psi p$ from the gluonic excitation (GlueX) experiment are fitted in a search for the exotic $P_c(4312)^+$ state observed by the Large Hadron Collider beauty (LHCb) Collaboration. The integrated luminosity of this GlueX experiment was about 320 pb^{-1}. The fits show that destructive interference involving an S-wave resonance and associated nonresonance background produces a sharp dip structure about 77 MeV below the LHCb mass, in the same location as a similar structure is seen in the data. Limitations of the employed model and the need for improved statistics are discussed.

I. INTRODUCTION

The formation of hadrons from quarks and gluons is governed by quantum chromodynamics (QCD). The traditional quark model [1,2], where hadrons are classified as mesons (composed of $q\bar{q}$) and baryons (composed of qqq), has provided a satisfactory description of the hadrons observed over the past 75 years. However, the past two decades have witnessed the emergence of states or resonant structures in experiments, many of which do not fit the hadron spectrum predicted by the naive quark model and thus are candidates to be exotic states. In particular, the Large Hadron Collider beauty (LHCb) experiment has reported the observation of four narrow P_c^+ pentaquark states in decays

$$\Lambda_b^0 \to J/\psi + p + K^-,$$

$$\Lambda_b^0 \to J/\psi + p + \pi^-,$$

and

$$B_s^0 \to J/\psi + p + \bar{p},$$

with hidden heavy charm quark contributions [3–6]. The masses of these four narrow P_c states, as well as their significance, are given in Table I. In response, many theoretical analyses evaluated these cases (see, for instance,

Refs. [7–17]). In particular, in Refs. [7–10], it was proposed to search for this P_c state in the J/ψ photoproduction off the nucleon. The corresponding cross section was evaluated based on the vector meson dominance model [18–20].

II. BACKGROUND

The gluonic excitation (GlueX) experiment measured total cross sections for the reaction $\gamma + p \to J/\psi + p$ and reported no evidence for the LHCb pentaquark candidates P_c^+ (Fig. 1) and set model-dependent upper limits on their branching ratios [21].

These interpretations of the LHCb and GlueX cases considered a constructive interference between a resonance and a nonresonant background for a particular wave, L^J (here, L is a total orbital momentum and J is the total angular momentum). In this work, we relax this requirement and consider the possibility of destructive interference as well.

New higher-statistics GlueX measurements of the threshold total cross section, for the reaction $\gamma + p \to J/\psi + p$ [22], motivate an alternative search for the LHCb exotics. The integrated luminosity of this recent GlueX experiment was about 320 pb^{-1}, a large improvement over the approximately 68 pb^{-1} of the GlueX data presented in Ref. [21]. Within the limits of the available statistics, the clearest structure is a dip observed in the recent GlueX total $\gamma + p \to J/\psi + p$ cross sections, in the vicinity of $W = 4.2$–4.3 GeV [22] (Fig. 2), a possible indication of the lowest-lying LHCb $P_c(4312)$ [5]. This dip becomes more pronounced in the new GlueX data [22] versus the initial GlueX report [21]. We therefore consider whether simple background or resonance interference is capable of reproducing the low-energy behavior visible in the cross-section data. Through interference, the cross section can develop either a peak or a dip. Pedagogical reviews of quantum interference are given in Refs. [23,24].

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TABLE I. Summary of P_c^+ properties reported by the LHCb Collaboration [5,6], where $\Gamma[P_c \to J/\psi + p]$ is representing the total width of the resonance.

State	M (MeV)	$\Gamma[P_c \to J/\psi + p]$ (MeV)	Significance
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$7.3\,\sigma$
$P_c(4337)^+$	4337^{+7+2}_{-4-2}	29^{+26+13}_{-12-14}	$3.1\text{–}3.7\,\sigma$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$5.4\,\sigma$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$5.4\,\sigma$

A general expression for the total cross section of the inelastic binary reaction $\gamma + p \to J/\psi + p$ can be written as

$$\sigma_t = \int_0^{2\pi} \int_0^\pi \frac{d\sigma}{d\Omega} \sin\theta \, d\theta \, d\phi, \tag{1}$$

where θ and ϕ are the J/ψ polar and azimuthal production angles, respectively.

Phenomenologically, the total cross section (σ_t), using the Landau-Lifshitz normalization, [25] is

$$\sigma_t = \frac{\pi}{4k^2} \sum_{J=0}^\infty (2J+1) |f|^2, \tag{2}$$

where k is the photon momentum in the γp center-of-mass (c.m.) system.

For an s-channel resonance in the reaction $\gamma + p \to P_c^+ \to J/\psi + p$, in the considered partial wave L^J (Fig. 1), we separate the nonresonant (b) and resonance (R) parts in the partial amplitude (f) following Refs. [24,26]. Then for the dominant partial wave, we can write

$$f = b + R \exp(2i\alpha), \tag{3}$$

where α is the relative phase shift that is responsible for the interference between resonance (R) and nonresonant (b) components of the partial amplitude. The interference may be either positive (constructive) or negative (destructive). We make α a free parameter in our fit of the cross sections, not given by any theory. Let us note that the resonance can interfere differently in different decay channels, at least due to different properties of the corresponding backgrounds.

For the resonance part of the partial amplitude, f, we use a canonical relativistic Breit-Wigner parametrization:

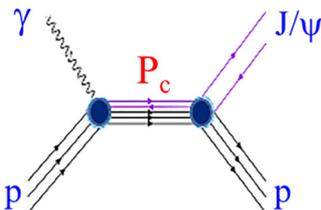$$R = \frac{2\Gamma M}{[(M)^2 - s] - i\Gamma M} X, \tag{4}$$

FIG. 1. s-channel resonance P_c.

where s is the square of the total energy in c.m. Then, M, Γ, and X are respectively the mass and total and partial widths

$$X = \frac{\sqrt{\Gamma(\gamma + p)\,\Gamma(J/\psi + p)}}{\Gamma}$$
$$= \sqrt{X(\gamma + p)X(J/\psi + p)} \tag{5}$$

of a particular resonance. Here, $\Gamma(\gamma + p)$ and $\Gamma(J/\psi + p)$ are the partial decay widths of the resonance P_c into two-particle channels, $P_c \to \gamma + p$ and $P_c \to J/\psi + p$, respectively. Since the width Γ of P_c is rather small, we assume a width with no energy dependence avoiding the need to modify the Breit-Wigner parametrization with additional form factors, leaving just three free resonance parameters M, Γ, and X to fit.

Traditionally, the total cross-section behavior vs energy of the near-threshold binary inelastic reaction $m_a + m_b < m_c + m_d$ is described as a series of *odd* powers in q (*even* powers in the case of elastic scattering), as we used for the $J/\psi - p$ scattering length determination recently [27]:

$$\sigma_t = Aq + Bq^3 + Cq^5, \tag{6}$$

where A, B, and C are free parameters and q is the c.m. momentum of the vector meson in the $J/\psi - p$ system. The *linear* term is determined by two independent S waves only with the total spin $1/2$ and/or $3/2$. Contribution to the *cubic* term comes from both P-wave amplitudes and energy dependence of S-wave amplitudes. Then, the fifth-order term arises from D waves and energy dependencies of S and P waves. The phenomenological study of the $J/\psi - p$ scattering length, using GlueX data [21], has shown that parameters B and C are consistent with zero (within uncertainties) [27]. For that reason, for the background (nonresonant) amplitude, we use just a *linear* and a *cubic* term from Eq. (6):

$$b = \sqrt{Aq + Bq^3}. \tag{7}$$
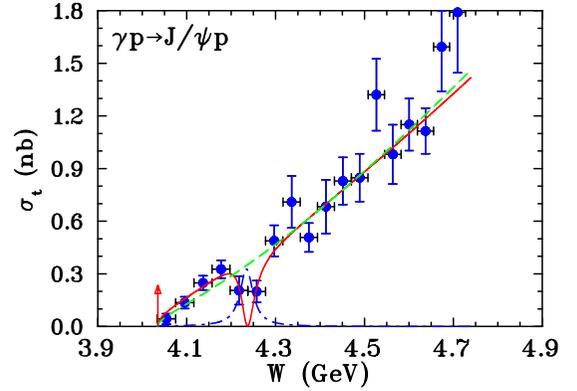

FIG. 2. Best-fit results for new GlueX total cross sections for the reaction $\gamma + p \to J/\psi + p$ (blue solid circles) [22]. The vertical error bars represent the total uncertainties (statistical and point-to-point systematic uncertainties in quadrature). The horizontal error bars reflect the energy binning (not used in the fit). The best-fit result, using Eq. (3), shown by the red solid curve. The green dashed curve corresponds to the nonresonant fit as a function of q [Eq. (7)]. The blue dash-dotted curve corresponds to the S-wave resonance. The red vertical arrow indicates the J/ψ production threshold ($W = 4.035$ GeV).

TABLE II. Best-fit results for the new GlueX data using Eq. (2). The second column presents results for statistical and point-to-point systematic uncertainties, which are combined in quadrature.

Quantity	Units	Parameter
M	MeV	4235 ± 8
Γ	MeV	35.4 ± 8.2
X		0.023 ± 0.005
α	deg	40.8 ± 5.7
A	nb GeV/c	$0.000\,251 \pm 0.000\,046$
B	nb/(GeV/c)	$0.000\,688 \pm 0.000\,083$

III. PHENOMENOLOGICAL FIT

In general, three other (higher mass) P_c's should reveal themselves in the $\gamma + p \rightarrow J/\psi + p$ cross section. This would require better statistics and a finer energy binning. If the GlueX Collaboration treats the two total cross-section points in the vicinity of $W = 4.2$–4.3 GeV as a potential dip (taking into account statistical and point-to-point systematic uncertainties), the probability that they are not a statistical fluctuation from an underlying smooth fit to the observed cross sections corresponds to a significance of $2.6\,\sigma$ [22]. However, if one considers the probability for any two adjacent points in the whole energy interval ($W = 4.05$–4.71 GeV) to have a deviation of at least this size, the significance reduces to $1.4\,\sigma$ [22].

Because the current statistics of the GlueX measurements 2270 ± 58 data [22] is by a factor of about 5 higher than the recently published 469 ± 22 [21], let us look for the effect of the LHCb low-lying P_c through the destructive interference of the S-wave resonance and the associated nonresonance background.

IV. RESULTS AND DISCUSSION

The best-fit results for new GlueX total cross sections for the reaction $\gamma + p \rightarrow J/\psi + p$ [22], using Eq. (2), is given in Table II and is shown in Figs. 2 and 3. Additionally, we found a sensitivity to the relative phase shift α.

Excluding a resonance contribution from Eq. (3), one can get the following result for the nonresonant contribution, using Eq. (7):

$A = (0.000\,183 \pm 0.000\,040)$ nb GeV/c,

$B = (0.000\,766 \pm 0.000\,077)$ nb/(GeV/c).

There is reasonable agreement between nonresonant parameters of two fits.

There were six free parameters for the $P_c(4312)^+$ resonance in the S-wave case and the overall χ^2/ndf $= 11.99/12 = 1.00$. The best-fit for the alternative hypothesis (just the nonresonant case) gives χ^2/ndf $= 19.74/16 = 1.23$. The A parameter is very small and in agreement with a very small $J/\psi - p$ scattering length determined recently [27–29] (Note that the parametrization of σ_t in the previous paper [27] does not include the factor of $\pi/4k^2$ in Eq. (2), which is equal to 0.169 GeV^{-2} at threshold). Overall, our phenomenology does not allow us to select a particular partial wave for the $P_c(4312)^+$ resonance (S or P wave). To get a P-wave $P_c(4312)$
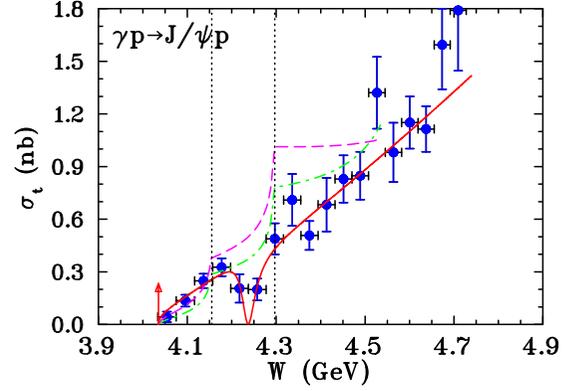

FIG. 3. The GlueX total cross section for the $\gamma + p \rightarrow J/\psi + p$ photoproduction (blue solid circles) [22]. The open charm model predictions [28] shown by the magenta dashed (green dash-dotted) curve with $q_{max} = 1$ GeV/c ($q_{max} = 1.2$ GeV/c). This model does not fit the GlueX data and has no normalization factor. The phenomenological best-fit result using Eq. (3) is shown by the red solid curve. Vertical black dotted lines show $\Lambda_c \bar{D}^{(*)}$ thresholds. The red vertical arrow indicates the J/ψ production threshold ($W = 4.035$ GeV).

resonance partial width, one needs $X/\sqrt{3}$ and $A/\sqrt{3}$ with $B/\sqrt{3}$.

V. CONCLUSION

Here we have shown that a resonancelike structure is "plausible" in the GlueX data [22], in an energy region close to the low-mass LHCb pentaquark [5,6]. The shift in masses between GlueX and LHCb results (77 MeV) may depend on the reaction mechanism [including cusps (open charm) and background choices]. One should note that if a "bump" is imposed on the GlueX data "by hand" (consider the 7th–9th energy values up from threshold), a qualitative description of the data up to 4.35 GeV is possible, but with a higher χ^2, if the above fit form is used. The obtained mass in our analysis is almost 77 MeV below the LHCb determination, but we cannot exclude that this is $P_c(4312)^+$. The statistics of the present GlueX data shown in Figs. 2 and 3 is not sufficient to draw a definite conclusion.

We conclude with an admission that the analytical structure in the vicinity of the LHCb P_c resonances is not as simple as a resonance plus background treatment would suggest. There are additional contributions to the P_c effect associated with the open charm impact [28]. In particular, the $\Lambda_c \bar{D}^{(*)}$-cusp effects could be visible. Actually, the interference between open charm and gluon exchange may (by some accident) produce a dip (see Fig. 3), but there is room for the resonance. The green dash-dotted curve ($q_{max} = 1.2$ GeV/c) reasonably agrees with the new GlueX data. While not evident in the GlueX data, one cannot exclude that we have all four LHCb P_c resonances [5] together with open charm and gluon exchange (gluon contribution can be strongly suppressed due to the "young" effect [30]; details about the "young" effect in the vector meson and nucleon interaction at the threshold are given in Ref. [31]). Complicated interference between these different components should motivate new high-statistics experiments.

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