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Puzzle for the Vector Meson Threshold Photoproduction

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High-statistics total cross sections for the vector meson photoproduction at the threshold: $\gamma p \to \omega p$ (from A2 at MAMI and ELPH), $\gamma p \to \phi p$ (from CLAS6 at JLab) and $\gamma p \to J/\psi p$ (from GlueX at JLab) allow one to extract the absolute value of vector meson nucleon scattering length using Vector Meson Dominance (VMD) model. The "young" vector meson hypothesis may explain the fact that the obtained scattering length value for the nucleon ϕ-meson compared to the typical hadron size of approximately 1 fm indicates that the proton is more transparent for the ϕ-meson compared to the ω-meson and is much less transparent than the J/ψ-meson. The extended analysis of Υ-meson photoproduction using quasi-data from the QCD approach is in perfect agreement with the light-meson findings using experimental data.

Recent high-statistical J/ψ photoproduction cross sections measured by the GlueX Collaboration allow us to search for the exotic $P_c(4312)$ state observed by the LHCb Collaboration. The fits show that destructive interference involving a S wave resonance and associated nonresonance background produces a sharp dip structure approximately 77 MeV below the LHCb mass, in the same location as a similar structure is seen in the data. The interference between open charm and gluon exchange may (by some accident) produce a dip, but there is room for resonance.

Future high-quality experiments by EIC and EicC will have the opportunity to evaluate cases for J/ψ- and Υ-mesons. It allows us to understand the dynamics of $c\bar{c}$ and $b\bar{b}$ production at the threshold and to look for the effect of LHCb $P_c(4312)$. The ability of J-PARC to measure $\pi^- p \to \phi n$ and $\pi^- p \to J/\psi n$, which are free from the VMD model, is evaluated.

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1. Introduction

There are no vector-meson (V) beams, so experiments in modern electromagnetic (EM) facilities attempt to access VN interactions via EM production reactions $ep \to e'Vp$. In the vector meson dominance (VMD) model, a real photon can fluctuate into a virtual V, which subsequently scatters off a target nucleon [1–3]. VMD does not contain any free parameters and can be used for a variety of qualitative estimates of observables in photo- and electro-production at least as a first step towards their more extended theoretical studies.

Some Vs can, compared to other mesons, be measured with very high precision. This comes from the fact that Vs have the same quantum numbers as a photon: $I^G(J^{PC}) = 0^-(1^{--})$. Let us focus on 4 Vs ($\omega$, ϕ, $J/\psi(1S)$, and $\Upsilon(1S)$) from $q\overline{q}$ nonet, the widths of which are narrow enough to study meson photoproduction at threshold and where data and quasi-data are available. To avoid broad width problems at threshold, we are not considering the ρ-meson case to determine the ρN scattering length (SL). Furthermore, we will ignore, for example, $\psi'(2S)$ due to the difference between the 1S and 2S states due to "zero" in radial wave functions (WFs).

2. Vector Meson Nucleon Scattering Length

Positive or negative VN SL may indicate a weakly repulsive or attractive VN interaction if there is no VN bound state below experimental q_{min} (here, q_{min} is the V center-of-mass momentum). For evaluation of the absolute value of VN SL, we apply the VMD model that links the near-threshold photoproduction cross sections of $\gamma p \to Vp$ and elastic $Vp \to Vp$. Finally, the absolute value of the VN SL can be expressed as a product of the kinematic factor driven by the pure VMD of the EM and the hadronic factor determined by the interaction of EM and the strong (hadronic) dynamics [4, 5]. To avoid theoretical uncertainties, we do not (i) determine the sign of SL, (ii) separate real and imaginary parts of SL, and (iii) extract spin 1/2 and 3/2 contributions.

Due to the small size of "young" V vs "old" V, measured and predicted SL is very small (Fig. 1). V created by the photon at the threshold then is probably not completely formed, and its radius is smaller than that of normal ("old ') V. Therefore, a stronger suppression for the Vp interaction is observed [12]. $p \to V$ coupling $q\overline{q}$ is proportional to α_S and the separation of the corresponding quarks. This separation (with a zero approximation) is proportional to $1/m_V$, where m_V is the mass of V. Then the "young" V hypothesis may explain the dependence of VN SL vs. the inverse mass of V, as Fig. 1 shows.

All previous theoretical results (including potential approaches and LQCD calculations) gave a much larger SL. Most probably such a large SL results from large distances in the tail of the van der Waals potential that in QCD should be killed by confinement [13].

3. High Energy and LQCD for ϕ at Threshold

The $N\phi$ SL became attractive these days. Recently, ALICE Collaboration has deduced the spin averaged ϕ N SL from the two-particle momentum correlation function [14]. The attractive SL value is close to 1 fm. In fact, ALICE is doing two-particle correlations of combined pairs $p\phi$ and $\overline{p}\phi$ measured in high multiplicity in collisions pp in W = 13 TeV. In addition, the final-state

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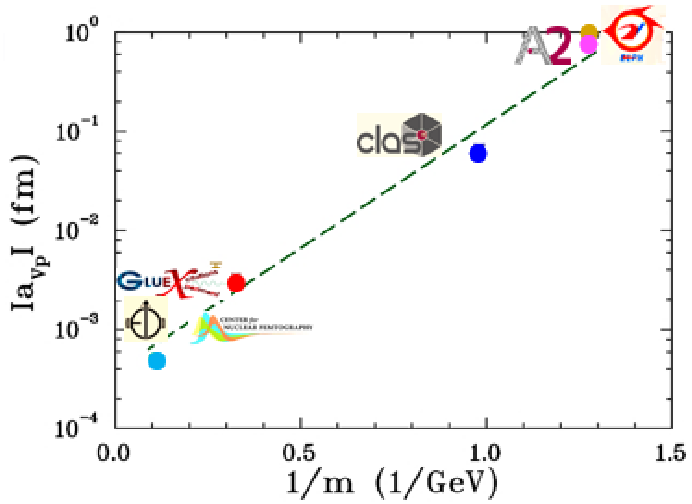

Figure 1: Comparison of the $|\alpha_{Vp}|$ SLs determined from V photoproduction at threshold vs the inverse mass of the Vs. The magenta (brown) filled circle shows the analysis of the A2 (ELPH) ω-meson data [6] ([7]), the blue filled circle shows the analysis of the CLAS ϕ-meson data [5, 8], the red filled circle shows the analysis of the GlueX J/ψ-meson data [4, 9], and the cyan filled circle shows the analysis of Υ-meson quasi-data for the EIC and EicC [10, 11]. The green dashed line is hypothetical.

interaction (FSI) correlation C(k) depends on the production mechanism. Then, ALICE assumes that the proton and ϕ -meson are produced independently at the $\sim$ 1 fm distance. Another problem is that it is practically impossible to observe $p\phi$ (or any pV) correlation (with very small $p\phi$ energy, *i.e.*, near threshold) at CERN (with ALICE or another detector).

Using (2 + 1)-flavor lattice QCD simulations with nearly physical quark masses, HAL Collaboration has simulated a $N\phi$ scattering process for the spin 3/2 channel [15]. The results are compatible with recent ALICE ϕN SL data. Instead of the ϕ photoproduction process, HAL simulated the ϕN elastic scattering reaction. It seems that the ϕN system is assumed as "in the lattice" and this result is a "numerical experiment." Using lattice calculations for the spin 3/2 ϕN interaction, HAL Collaboration is used to constrain the spin 1/2 counterpart from the fit of the experimental correlation function ϕp measured by ALICE [16]. The corresponding SL is compatible with recent spin 3/2 by the HAL and ALICE results. The combination of the lattice spin 3/2 and 1/2 result gives a huge $p\phi$ SL.

4. How Unique LHCb P_c Evidences

QCD [17, 18] gives rise to hadron spectrum. Many $\overline{q}q$ and qqq have been observed [19], while $\overline{q}q\overline{q}q$ and $qqq\overline{q}q$... are not forbidden or we do not yet know them. Recently LHCb claimed evidence for three hidden-charm $qqq\overline{c}c$ states near open-charm decay thresholds for $\Sigma_c^+\overline{D}^0$ and $\Sigma_c^+\overline{D}^{*0}$ in $\Lambda_b^0 \to J/\psi + p + K^-$ and $\Lambda_b^0 \to J/\psi + p + \pi^-$ decays with hidden heavy-charm quark contributions [20]. In response, many theoretical analyses evaluated these cases.

The first attempt to search for LHCb resonances P_cs was made by the GlueX Collaboration in photoproduction of the proton J/ψ [9]. This bump-hunting search found no evidence for LHCb P_cs, just gave the upper limits at 90% confidence level (CL). The data samples of 102 million $\Upsilon(1S)$

events collected by the Belle Collaboration then do not provide significant evidence for LHCb P_cs in pJ/ψ final state in inclusive $\Upsilon(1S)$ decay [21]. A search for a hidden charm pentaquark state that decays to a range of $\Sigma_c\overline{D}$ and $\Lambda_c^+\overline{D}$ final states and using pp collision data at W = 13 TeV found that the signal yield of known LHCb P_c s is consistent with zero in all cases [22].

One cannot believe that these new results [9, 21, 22] may "kill" hidden charm LHCb states [20]. The point is that we do not know the theoretically expected cross sections and branching ratios. Now, these experimental data are just some additional constraints on pentaquark models.

An amplitude analysis of untagged flavor decays $B_s^0 \to J/\psi + p + \overline{p}$ is performed using collision data pp by the LHCb Collaboration [23]. Evidence for a new structure in $J/\psi p$ and $J/\psi\overline{p}$ with mass 4337 MeV and width 29 MeV is found with a significance of approximately 3.4σ. It can be excluded that $P(4337)$ [23] is the same as $P(4312)$ [20]. The mass change may depend on the reaction mechanism and background choices because the mass resolution is much better than 10 MeV, while the mass difference is 4337 - 4312 = 25 MeV.

Furthermore, an amplitude analysis of the decays of $B^- \to J/\psi\Lambda\overline{p}$ is performed using 4400 signal candidates selected on a data sample of collisions pp recorded at W = 7, 8, and 13 TeV with the LHCb detector [24]. The mass of this new $J/\psi\Lambda$ state is determined to be 4338 MeV (close to the $\Xi_c^+ D^-$ threshold) with a significance of > 10σ. That is the first observation of a pentaquark with strange-quark content: $ccud\bar{s}$.

5. Quantum Interference

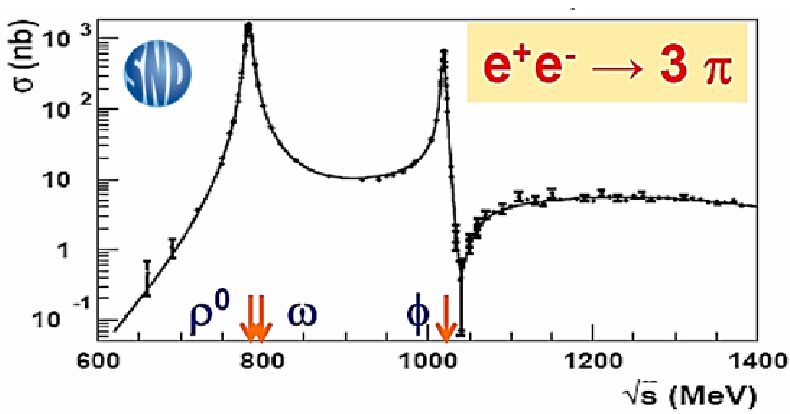

Figure 2: The $e^+e^- \to \pi^+\pi^-\pi^0$ cross section measured by the SND group and collected in [26]. The curve is the fit with the ω-, ϕ-, ρ^0-, ω'- and ω''-mesons.

The interference of resonances has not only academic interest. Even now it has applications, *e.g.*, to the search for and study of rare decay modes of well-known resonances [25]. The same phenomenon may be seen in complementary variables - energy (mass in rest frame): it is seen as deformation of Breit-Wigner (BW) peaks. As an illustration, Figure 2 shows the cross section for reaction $e^+e^- \to \pi^+\pi^-\pi^0$ as a function of energy (mass). Experimental data on this reaction, measured by the SND group, are collected in [26]. At first sight, the contribution of ρ^0 should always be negligible compared to the contribution of ω. This is true indeed near the vertex of the BW peak, but may not be true for the BW tails because of very different total widths. The large ρ^0

width, which is approximately 18 times larger than the ω width, suggests a slower decrease in the ρ^0 BW tails compared to the ω-ones. As a result, the (ρ^0, ω)-interference in $e^+e^- \to \pi^+\pi^-\pi^0$ is quite negligible near the vertex of the BW peak, but may be noticeable for the BW tails [25].

6. Alternative Solution for GlueX J/ψ Data

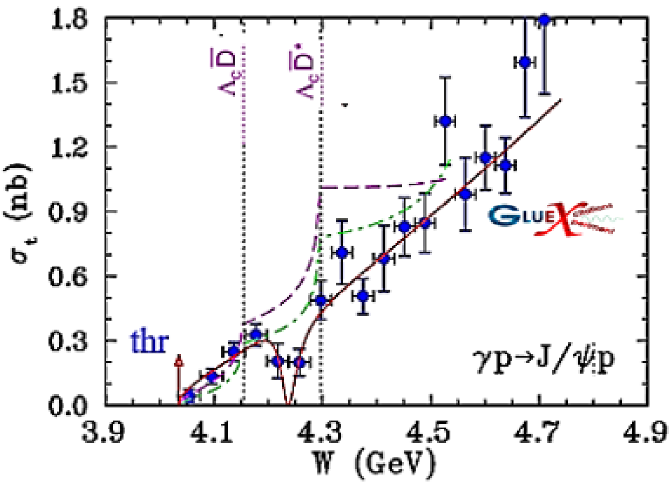

Figure 3: The GlueX total cross section for the $\gamma p \to J/\psi p$ photoproduction (blue filled circles) [27]. The best phenomenological fit result is shown by the solid red curve [28]. The predictions of the open charm model [29] are shown by the magenta dashed (green dash-dotted) curves with q_{max} = 1 GeV/c (q_{max} = 1.2 GeV/c). This model does not fit the GlueX data and has no normalization factor. The black vertical dotted lines show the $\Lambda_c\overline{D}^{(*)}$-thresholds. The vertical red arrow indicates the production threshold J/ψ (W = 4.035 GeV).

New high-statistics total cross-section data for $\gamma p \to J/\psi p$ from the GlueX experiment [27] is fitted to a search for the exotic $P_c(4312)^+$ state observed by the LHCb Collaboration in the reaction $\Lambda_b \to J/\psi p K^-$ [23]. We suggested applying rearrangement interference to reveal faint resonance signals (amplification by interference with a strong background signal) [28]. The fit of the GlueX data shows that destructive interference involving an S-wave resonance and associated non-resonance 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 GlueX data [27] (Fig. 3). The dip position does not correspond to the real mass of $P_c(4312)^+$. It may depend on the reaction mechanism [including cusps (open charm)] and background choices. The interference between open charm and gluon exchange can produce a small dip [29], but there is room for resonance [28] (Fig. 3). Limitations of the model [28, 29] used and the need for improved statistics.

7. CLAS12 Electroproduction for ϕ at Threshold

ϕ-meson electroproduction database (DB) is limited and there are no threshold measurements which are suitable to evaluate ϕN SL vs Q^2. New CLAS12 data for the electroproduction of ϕ on the proton, $ep \to e'\phi p$, at the 11 GeV beam energy with the CLAS12 spectrometer will be forthcoming [30]. The kinematic range extends in W from the ϕ-meson threshold, 1.96 GeV, to

5 GeV, Q^2 from 1 to 12 GeV^2, and $|t - t_{min}|$ from near zero to $\sim$ 4 GeV^2. Evaluation Q^2 of the $N\phi$ SL is important to understand the dynamics of $s\bar{s}$ production at the threshold.

8. J-PARC Pion Induced Measurements

The total cross sections were predicted for the pion-induced reactions $\pi^- p \to \phi n$ and $\pi^- p \to J/\psi n$ at low energies [31] and the difference in the cross sections has a factor of 10^6 (Fig. 4). Unfortunately, there are no data at the threshold for both reactions. The E45 proposal to measure the cross sections for the reaction $\pi^- p \to \phi n$ in J-PARC is available [32]. Data can be described very well by linear fit. This is due to the S wave dominance of the total cross sections. From the slope of the best-fit line, the restriction can be found in the imaginary part of the elastic scattering amplitudes of $A_{\phi n}$ and $A_{J/\psi n}$. As was done for $\pi^- p \to \eta n$ [33]. The J-PARC measurements allow us to understand the dynamics of the production of $s\bar{s}$ and $c\bar{c}$ at threshold. It is free from VMD and allows us to determine ϕp and $J/\psi p$ SLs independently of VMD. Furthermore, it also allows us to look for the effect of LHCb P_cs.

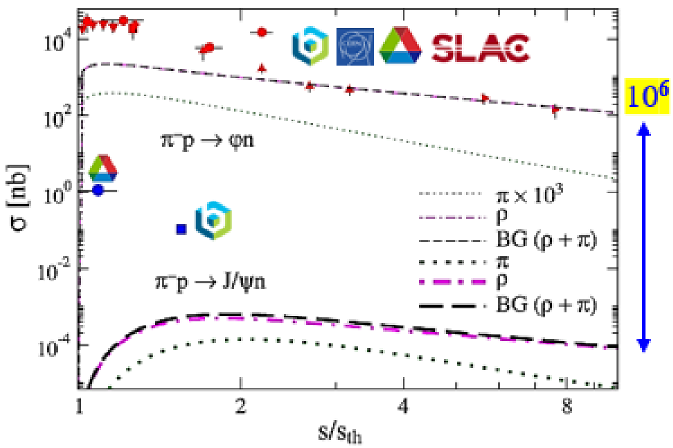

Figure 4: Contributions to the total cross sections for the reactions $\pi^- p \to \phi n$ and $\pi^- p \to J/\psi n$ with ρ and π Reggeon exchanges [31]. The logos of the collaborations show the sources of data.

9. Conclusions and Outlook

"Young" V hypothesis may explain fact that obtained SL value for the ϕ-meson nucleon compared to the typical hadron size of 1 fm indicates that the proton is more transparent for the ϕ-meson compared to the ω-meson and is much less transparent that J/ψ- and Υ-meson. Future high-quality experiments by EIC and EicC will have the opportunity to evaluate physics for J/ψ- and Υ-mesons. It allows us to understand the dynamics of $c\bar{c}$ and $b\bar{b}$ production at threshold and to look for the effect of LHCb $P_c(4312)$. The ability of J-PARC to measure $\pi^- p \to \phi n$ and $\pi^- p \to J/\psi n$ at VMD-free thresholds is an important input in phenomenology [partial wave analysis (PWA)]. Polarized measurements are an important contribution for model-independent PWA.

There are plenty of works for theoreticians and experimentalists, in particular, on the nature of the LHCb states. Hadronic Molecules or Compact Pentaquarks (real exotics). We assume that these states exist.

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