$J/\psi$ and XYZP photo production

Adam Szczepaniak (IU/JLab)

- Quarkonium near threshold possibly relevant for extracting novel nucleon properties (mass radius, gravitational form factors, etc.)

- Signal channel also contains hidden-charm pentaquark candidates seen at LHCb.

- Abundance of new data coming from Jefferson Lab on energy and angular dependence of x-section.

- New window onto the nature of the XYZ states.
• Established in 2013 to develop theory and phenomenology in support of experimental program at JLab12.

• JPAC served as a liaison between many theoretical and experimental analysis efforts BaBar, BESIII, COMPASS, EIC, LHCb, JLab

• Over 40 researchers have been associated with JPAC.

• Focus on light exotic hybrids — predicting their properties from lattice QCD

— extracting meson resonances from experimental data

— interpreting both the experiment and theoretical results
Exp and Theory are working together

- Over the past 50 years data has improved dramatically
- It allows model independent analysis

Similar spectra expected from CLAS12
Model independent analysis

Nature: real axes

QCD

Model independent (based on S-matrix principles)

Models
Amplitude analysis

1. Amplitudes are analytical functions of $s_1, \cdots t_1, \cdots$

2. Partial wave amplitudes are analytical functions angular momentum $f_l(s) = f(l, s)$

3. Physical sheet singularities are given by unitarity

4. Unphysical sheet singularities need to be parametrized in order to test microscopic models
Holy Grail: AI as a tool for physics discovery

Learn (S-matrix)

$S = T \exp \left( -i \int_{-\infty}^{\infty} dt H'(t) \right)$

Apply to data

Tell the story

"Deep learning exotic hadrons" L.Ng et al. (JPAC) Phys.Rev.D 105 (2022) 9, L091501
Importance of high quality data: split a2

\[ \pi^- + p \rightarrow X^- + p \]

The puzzle of the A2 meson

The A2 may be two distinct but similar particles or a single object of an entirely new type. Either way, it has experimentalists arguing and theorists confused.

Proton-antiproton annihilation shows evidence for a split A2. The dip at the A2 (mass)², shown by the colored arrow, in the K⁺K⁻ effective mass spectrum indicates that the A2 splitting is independent of the production reaction. The data were taken by a CERN-College de France-Liverpool bubble-chamber group.

1965-1970
\[ \text{split } P_c \]

**LHCb, Run 1, 2015**

**LHCb, Run 1+Run 2, 2019**

\[ P_c(4450) \rightarrow P_c(4440) + P_c(4457) \]
Many XYZ’s are unconfirmed but some appear more “real” than others.

- $T_{\psi\psi}$ or $X(6900)$ a $\psi\psi$ resonance ($c\bar{c}c\bar{c}$)?

**XYZP’s: real or not?**

\[ X(3872) (\chi_{c1}(3872)) \]

**Remark on Energy Peaks in Meson Systems**

If the width of particle \( X \) is not very large we will stay close to the physical region. This almost singular behavior of \( A(s) \) for certain physical \( s \) causes the peaking effect to which we refer as an \((X, Y, Z)\) peak.

\[ \vec{q}^2 \mu^2 = -1 + \frac{\mu^2}{\mu^2 + \vec{q}^2} \]

**Attractive = Attractive + Repulsive**

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**Very close to \( DD^* \) threshold**

Is \( X(3872) \) a molecule?

\[
M_{X(3872)} - M_{D^0} - M_{D^{*0}} = -0.01 \pm 0.14 \text{MeV}
\]
DIRECT DETERMINATION OF A SHORT NUCLEAR LIFETIME ($\approx 10^{-20}$ s) 
BY THE PROXIMITY SCATTERING METHOD

J. LANG, R. MÜLLER, W. WÖLFLI, R. BÖSCH and P. MARMIER
Laboratorium für Kernphysik, Eidg. Techn. Hochschule, Zürich

Received 4 February 1966

$\beta + t \to 1 + 2 + 3$, 
$[d + ^{12}\text{C} \to n + p + ^{12}\text{C}]$, 

$\beta + t \to 1 + R$, with $Q$-value $Q_1$ 
$[d + ^{12}\text{C} \to n + ^{13}\text{N}^*$, 
$Q_1 = -3.82$ MeV$]$, 

$R \to 2 + 3$ with $Q$-value $Q_2$ 
$[^{13}\text{N}^* \to p + ^{12}\text{C}]$, 
$Q_2 = 1.59$ MeV$, $
Triangles are everywhere

COMPASS, 2021

LHCb 2019

$\sim 0.1 \%$

$1^{+}0^{+} f_{0}(980) \pi P$

$0.1 < t' < 1.0 \text{ (GeV}/c)^2$

(1) Model curve
(2) $a_{1}(1420)$ resonance
(3) Non-resonant term

$a_{1}(1460)$

$\Gamma_{\ell} = 50 \text{ MeV}$

Burns, Swanson
Kinematic reflections

Are the Z’s true resonances or kinematic effects

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Kinematic effects from K* decays?

\[ B \rightarrow \psi' \pi^- K^+ \]

\[ Z^- K^+ \rightarrow \psi' \pi^- K^+ \]
Understanding production cont.

*XYZP* spectroscopy at a charm photoproduction factory


EIC/JLab++ explore the complementarity of diffraction, peripheral and/or direct production.
Spectroscopy at the future facilities

$Z^+$, Production @JLab++, EIC

- Couplings from data as much as possible, not relying on the nature of XYZ
- The model is expected to hold in the highest $x$-bin
- Model underestimates lower bins, conservative estimates

### Table I: Estimates of yields for day of data taking at CLAS24 assuming a zero-angle electron detector

<table>
<thead>
<tr>
<th>Meson</th>
<th>Cross Section (nb)</th>
<th>17 GeV</th>
<th>24 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(3900)^+$</td>
<td>2.2 k</td>
<td>371 k</td>
<td>4.2 k</td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>1.1 k</td>
<td>32 k</td>
<td>4.2 k</td>
</tr>
</tbody>
</table>

### Table II: Summary of results for production of some states of interest at the E11 electron and proton beam momentum $5 \times 10^9 (GeV/c)$ (for electron x proton). Columns show: the meson name; our estimate of the total cross section; production rate per day, assuming a luminosity of $6.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$; the decay branch to a particular measurable final state; its ratio; the rate per day of the meson decaying to the given final state.

- $\gamma p \rightarrow b_1^+ X$
- $Z_c^- \Delta^{++}$
- $Z_c^+ n$

https://github.com/dwinney/jpacPhoto

D. Winney et al. (JPAC)

M. Albaladejo et al. [JPAC], PRD (2020)
• Production at EIC

<table>
<thead>
<tr>
<th>Constituents</th>
<th>$I, J^{P(C)}$</th>
<th>EiC</th>
<th>EiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>$D\bar{D}^*$</td>
<td>0, 1$^{++}$</td>
<td>21(89)</td>
</tr>
<tr>
<td>$Z_c(3900)^0$</td>
<td>$D\bar{D}^*$</td>
<td>1, 1$^{+-}$</td>
<td>$0.4\times10^3$</td>
</tr>
<tr>
<td>$Z_{cs}$</td>
<td>$D^*\bar{D}_s$</td>
<td>1/2, 1$^+$</td>
<td>19(69)</td>
</tr>
<tr>
<td>$P_c(4312)$</td>
<td>$\Sigma\bar{D}$</td>
<td>1/2, 1/2$^-$</td>
<td>0.8(4.1)</td>
</tr>
<tr>
<td>$P_{cs}(4338)$</td>
<td>$\Sigma_c\bar{D}$</td>
<td>0, 1/2$^-$</td>
<td>0.1(1.6)</td>
</tr>
<tr>
<td>Predicted</td>
<td>$\Lambda_c\bar{\Lambda}_c$</td>
<td>0, 0$^{-}$</td>
<td>0.3 (3.0)</td>
</tr>
<tr>
<td>Predicted</td>
<td>$\Lambda_c\bar{\Sigma}_c$</td>
<td>1, 0$^-$</td>
<td>0.01 (0.12)</td>
</tr>
<tr>
<td>$T_{cc}^+$</td>
<td>$DD^*$</td>
<td>0, 1$^+$</td>
<td>$0.3\times10^{-3}$</td>
</tr>
</tbody>
</table>

Order-of-magnitude estimates of the semi-inclusive electro-production of hidden/double-charm hadronic molecules (in units of pb)

F-K Guo @ EIC Workshop
XYZP’s : real or not ?

Threshold effects ? Du et al, EPJC 80, 1053 (2020)

- "Dip" above 9 GeV has 2.6σ (1.3σ) local (global) significance
- Full GlueX-I data yields 2270 ± 58 J/ψ’s

Confirmation of gluon dominated dynamics? … but
• Two (distinct) approaches:
  
  — t-channel partial waves
  \[ A(s, t) = \sum_l f_l(t)P_l(z_t) \quad l_{\text{max}} \leq 2 \]
  smooth s-dependence
  
  — s-channel partial waves
  \[ A(s, t) = \sum_l f_l(s)P_l(z_s) \quad l_{\text{max}} \leq 3 \]
  s-channel thresholds

\[ J/\psi \text{ photo production} \]

\[ 007_{J/\psi} \]

\[ \text{GlueX} \]

- Kharzeev et al. (1999), Brodsky et al (2001), Ji et al., Guo et al. (2021), Z, Mamo, Zahed, (2020)
- GlueX [arXiv:2304.03845]
Fit results/conclusions

• “Exponential” behavior from the few lowest partial waves

\[ l_{\text{max}} \leq 3 \]

• The expected hierarchy of partial waves S>P>D>F with the flattening at larger-\( t \) accounted for by p.w interferences

FIG. 2: Fit results for the differential cross section compared to GlueX data from [37]. The bands correspond to the 1\( \sigma \) uncertainties from the bootstrap analysis.
Fit results/conclusions

- Elastic $\psi p \rightarrow \psi p$ scattering length $a_S \sim O(0.1 fm)$ found incompatible with VMD expectations (albeit with large errors)

- Inclusion of open charm reduces the discrepancy

- Fits also suggests relevance of open charm production and compatible with pentaquark production

- Need more precise data, including open charm production

FIG. 1: Fit results for the integrated cross section compared to GlueX data from [37]. Bands correspond to 1σ uncertainties from bootstrap analysis.
Discoveries of XYZP phenomena show there is a large “hadronic landscape” yet to be discovered (also in the light flavor sector).

Properly constrained S-matrix amplitude analysis can determine if these “exotic” states are real (e.g. true partial wave poles) or something else (e.g. kinematic artifacts).

At JLab++(EIC) yields are expected to be comparable to colliders at $\sim 10^{34}$ (higher luminosity, lower energy) and triggers optimized for charmonium final states;

Direct (photo) production needed for confirmation particularly true for the Z’s which so far seen only in 3body final states. Null results are as important as observations!

In a decade we will have a very different view of hadrons compared to that proposed by Gell-Mann and Zweig.