Study of radiative decays of the $\Upsilon(1S)$ and of three-body decays of the $J/\psi$ at BABAR

Patrick Robbe, LAL Orsay, for the BABAR Collaboration, 18 April 2018
Radiative and hadronic decays of quarkonium

• Radiative or hadronic quarkonium decays can be used to perform spectroscopy of light mesons ($f_J$, $K^*$, ...).
• They provide also a good laboratory to explore « exotic » QCD states like multiquark states or glueball (bound states of gluons).
• The lowest state $J^{PC}=0^{++}$ is expected to have a mass around 1.5 GeV/$c^2$, accessible in quarkonium decays.
• One possible candidate for this state could be the $f_0(1710)$ for which more experimental information is important.
• Good understanding of the decay characteristics is crucial: requires very low background which can be achieved for quarkonium produced in $e^+e^-$ collisions.
The BABAR experiment

- Asymmetric $e^+e^-$ collisions at 10.58 GeV center of mass energy: 0.5 ab$^{-1}$ i.e. $670 \times 10^6$ $c\bar{c}$ pairs for $J/\psi$ studies.
- 14 fb$^{-1}$ and 28 fb$^{-1}$ at $Y(2S)$ and $Y(3S)$ peaks.
Dalitz plot analysis of J/ψ decays

• Results on Dalitz plot analysis of the decays:
  • J/ψ → π⁺ π⁻ π⁰,
  • J/ψ → K⁺ K⁻ π⁰,
  • J/ψ → K⁰ s K⁺ π⁻ + charge conjugate.

• Produced via e⁺e⁻ annihilation with initial-state radiation (ISR):
  • Photon most of the time undetected.
  • Only J/ψ produced: no background from underlying event.

• Investigate these decays with large statistics:
  • J/ψ → π⁺ π⁻ π⁰ shows complex structure with high mass resonances which are investigated with models implementing Regge asymptotics (Veneziano models).
  • J/ψ → K⁰ s K⁺ π⁻ : first Dalitz plot analysis.
**J/ψ event selection**

- $J/\psi \rightarrow K_s^0 K^+ \pi^-$, $K_s^0 \rightarrow \pi^+ \pi^- \pi^0$: 4 tracks and $K_s^0$ distance to interaction point > 2 mm.
- $J/\psi \rightarrow \pi^+ \pi^- \pi^0$ and $J/\psi \rightarrow K^+ K^- \pi^0$: 2 tracks and $E(\gamma) > 100$ MeV.
- Particle identification for charged $K$ and $\pi$.
- To select $J/\psi$ coming from ISR events:
  - $\left| (p_{e^+} + p_{e^-}) - (p_{h^+} + p_{h^-} + p_\pi^0) \right|^2 < 2$ GeV$^2$ or $\left| (p_{e^+} + p_{e^-}) - (p_{K_s^0} + p_{K^-} + p_{\pi^+}) \right|^2 < 1.5$ GeV$^2$.
  - If ISR photon is in calorimeter acceptance, require measurement compatible with its properties.
- Background from $e^+e^- \rightarrow \gamma \pi^+ \pi^-$ rejected with $|\cos\theta_\pi| < 0.95$ where $\theta_\pi$ is helicity angle of pion for the $\pi\pi$ system.

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**Graphs**

- (a) $J/\psi \rightarrow \pi^+ \pi^- \pi^0$
  - 20000 events
  - 91% purity

- (b) $J/\psi \rightarrow K^+ K^- \pi^0$
  - 2100 events
  - 89% purity

- (c) $J/\psi \rightarrow K_s^0 K^+ \pi^-$
  - 3900 events
  - 93% purity
J/ψ branching fractions and Dalitz plots

\[ \mathcal{R}_1 = \frac{\mathcal{B}(J/\psi \to K^+ K^- \pi^0)}{\mathcal{B}(J/\psi \to \pi^+ \pi^- \pi^0)} = 0.120 \pm 0.003 \text{ (stat)} \pm 0.009 \text{ (syst)} \] [PDG: 0.133 \pm 0.038 [MARK II, PRL51 (1983) 963]]

\[ \mathcal{R}_2 = \frac{\mathcal{B}(J/\psi \to K_S^0 K^{\pm} \pi^{\mp})}{\mathcal{B}(J/\psi \to \pi^+ \pi^- \pi^0)} = 0.265 \pm 0.005 \text{ (stat)} \pm 0.021 \text{ (syst)} \] [PDG: 0.123 \pm 0.033 [MARK I, PRD15 (1977) 1814]]

With main systematic uncertainties from knowledge of efficiencies.
J/ψ → π⁺ π⁻ π⁰ isobar model

• Dalitz plot analysis in the J/ψ signal region, describing resonances by relativistic Breit Wigner shapes. Total of 8 free parameters.

<table>
<thead>
<tr>
<th>Final state</th>
<th>Amplitude</th>
<th>Isobar fraction (%)</th>
<th>Phase (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ(770)π</td>
<td>1</td>
<td>114.2 ± 1.1 ± 2.6</td>
<td>0.</td>
</tr>
<tr>
<td>ρ(1450)π</td>
<td>0.513 ± 0.039</td>
<td>10.9 ± 1.7 ± 2.7</td>
<td>−2.63 ± 0.04 ± 0.06</td>
</tr>
<tr>
<td>ρ(1700)π</td>
<td>0.067 ± 0.007</td>
<td>0.8 ± 0.2 ± 0.5</td>
<td>−0.46 ± 0.17 ± 0.21</td>
</tr>
<tr>
<td>ρ(2150)π</td>
<td>0.042 ± 0.008</td>
<td>0.04 ± 0.01 ± 0.20</td>
<td>1.70 ± 0.21 ± 0.12</td>
</tr>
<tr>
<td>ω(783)π⁰</td>
<td>0.013 ± 0.002</td>
<td>0.08 ± 0.03 ± 0.02</td>
<td>2.78 ± 0.20 ± 0.31</td>
</tr>
<tr>
<td>ρ(1690)π</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>127.8 ± 2.0 ± 4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>χ²/ν</td>
<td>687/519 = 1.32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• When leaving free the ρ(1450) and ρ(1700), the best fit is obtained for:

\[
m(\rho(1450)) = 1429 ± 41 \text{ MeV}/c^2, \\
Γ(\rho(1450)) = 576 ± 29 \text{ MeV}, \\
m(\rho(1700)) = 1644 ± 36 \text{ MeV}/c^2, \\
Γ(\rho(1700)) = 109 ± 19 \text{ MeV}.
\]

[PRD95 (2017) 072007]
J/ψ → π⁺ π⁻ π⁰ Veneziano model

- Veneziano model = alternative model to describe better the high mass region [Szczepaniak, Pennington, PLB737 (2014) 283].

\[ A(s, t, \lambda) = \varepsilon_{\mu \nu \rho \sigma} p_\mu^+ p_\nu^- p_\rho^0 \varepsilon(p_\psi, \lambda) \sum_{1 \leq m \leq n} \frac{\Gamma(n - \alpha(s)) \Gamma(n - \alpha(t))}{\Gamma(n + m - \alpha(s) - \alpha(t))} \]

\[ \alpha(s) = \alpha_0 + \alpha' s + i \gamma \sqrt{s - s_0} \]

- The model deals with Regge trajectories instead of single resonances. The complexity of the model is related to the number of trajectories, \( n \), to include in the fit. Here: \( n=7 \) i.e. 19 free parameters.

<table>
<thead>
<tr>
<th>Final state</th>
<th>Isobar fraction (%)</th>
<th>Veneziano fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho(770)\pi )</td>
<td>114.2 ± 1.1 ± 2.6</td>
<td>133.1 ± 3.3</td>
</tr>
<tr>
<td>( \rho(1450)\pi )</td>
<td>10.9 ± 1.7 ± 2.7</td>
<td>0.80 ± 0.27</td>
</tr>
<tr>
<td>( \rho(1700)\pi )</td>
<td>0.8 ± 0.2 ± 0.5</td>
<td>2.20 ± 0.60</td>
</tr>
<tr>
<td>( \rho(2150)\pi )</td>
<td>0.04 ± 0.01 ± 0.20</td>
<td>6.00 ± 2.50</td>
</tr>
<tr>
<td>( \omega(783)\pi^0 )</td>
<td>0.08 ± 0.03 ± 0.02</td>
<td>0.40 ± 0.08</td>
</tr>
<tr>
<td>( \rho_3(1690)\pi )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>127.8 ± 2.0 ± 4.3</td>
<td>142.5 ± 2.8</td>
</tr>
<tr>
<td>( \chi^2/\upsilon )</td>
<td>687/519 = 1.32</td>
<td>596/508 = 1.17</td>
</tr>
</tbody>
</table>

\(|\cos\theta_\lambda|<0.2 \]

Fit result Veneziano model
**J/ψ → K⁺ K⁻ π⁰** and **J/ψ → Kₛ⁰ K⁺ π⁻** results

- J/ψ → K⁺ K⁻ π⁰ can be used to extract

\[
\frac{B(ρ(1450)^0 → K^+K^-)}{B(ρ(1450)^0 → π^+π^-)} = 0.307 \pm 0.084 \text{ (stat)} \pm 0.092 \text{ (syst)}.
\]

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<table>
<thead>
<tr>
<th>Final state</th>
<th>fraction (%)</th>
<th>phase (radians)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^± K^±$</td>
<td>92.4 ± 1.5 ± 3.4</td>
<td>0.</td>
</tr>
<tr>
<td>$ρ(1450)^0 π^0$</td>
<td>9.3 ± 2.0 ± 0.6</td>
<td>3.78 ± 0.28 ± 0.08</td>
</tr>
<tr>
<td>$K^*(1410)^± K^±$</td>
<td>2.3 ± 1.1 ± 0.7</td>
<td>3.29 ± 0.26 ± 0.39</td>
</tr>
<tr>
<td>$K^*_2(1430)^± K^±$</td>
<td>3.5 ± 1.3 ± 0.9</td>
<td>-2.32 ± 0.22 ± 0.05</td>
</tr>
</tbody>
</table>

Total: 107.4 ± 2.8

χ²/ν: 132/137 = 0.96
Study of $Y(1S)$ radiative decays

- Radiative decays suppressed in $Y$ system compared to charmonium system: challenging analysis.

- Measurement of branching fractions and resonance structure of:
  - $Y(1S) \rightarrow \pi^+\pi^-\gamma$,
  - $Y(1S) \rightarrow K^+K^-\gamma$.

- $Y(1S)$ are produced from $Y(2S)$ and $Y(3S)$ decays in the modes $Y(2S) \rightarrow \pi^+\pi^- Y(1S)$ and $Y(3S) \rightarrow \pi^+\pi^- Y(1S)$ where the two pions are soft: this allows to obtain clean signal using the 13.6 fb$^{-1}$ and 28 fb$^{-1}$ of $Y(2S)$ and $Y(3S)$ on-resonance data.

- Branching fractions are normalized to the $Y(1S) \rightarrow \mu^+\mu^-$ decay for which are reconstructed:
  - $435000 \ Y(2S) \rightarrow \pi^+\pi^\ [Y(1S) \rightarrow \mu^+\mu^-]$,
  - $132000 \ Y(3S) \rightarrow \pi^+\pi^\ [Y(1S) \rightarrow \mu^+\mu^-]$. 

[arXiv:1804.04044]
Y(1S) event selection

- Exactly 4 charged tracks with $p_T > 100$ MeV/c.
- Exactly 1 photon with $E > 2.5$ GeV.
- Particle identification for charged $K$ and $\pi$.
- Momentum balance in the event, $\Delta p_i = p_i^{e^-} + p_i^{e^+} - (p_i^{\gamma} + p_i^{\pi^+} + p_i^{\bar{\pi}^+} + p_i^{h^+} + p_i^{h^-})$, should be close to 0.
- The recoiling mass to the two soft pions in $Y(2S) \rightarrow \pi^+\pi Y(1S)$ and $Y(3S) \rightarrow \pi^+\pi Y(1S)$, $M_{rec}^2 = |p_e^- + p_e^+ - p_{\pi^+} - p_{\pi^-}|^2$, should be close to the Y(1S) mass.

![Graphs of $Y(1S) \rightarrow \pi^+\pi\gamma$ and $Y(1S) \rightarrow K^+K^-\gamma$]
\[ \pi^+ \pi^- \text{ mass spectrum} \]

- Summed over the Y(2S) and Y(3S) samples.
- Fit with mass function sum of (16 free parameters):
  - \(s\)-wave term: sum of \(f_0(500)\) described by relativistic Breit Wigner and \(f_0(980)\) described by Flatté formalism.
  - \(f_2(1270)\) and \(f_0(1710)\) as relativistic Breit Wigner.
  - Combinatorial background.
  - \(\rho^0\) background for Y(3S) data, as indicated from mass sidebands.

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Resonances} (\pi^+ \pi^-) & \text{Yield } \Upsilon(2S) & \text{Yield } \Upsilon(3S) & \text{Significance (}\sigma\text{)} \\
\hline
S\text{-wave} & 133 \pm 16 \pm 13 & 87 \pm 13 \text{ (stat only)} & 12.8 \\
f_2(1270) & 255 \pm 19 \pm 8 & 77 \pm 7 \pm 4 & 15.9 \\
f_0(1710) & 24 \pm 8 \pm 6 & 6 \pm 8 \pm 3 & 2.5 \\
f_0(2100) & 33 \pm 9 \text{ (stat only)} & 8 \pm 15 \text{ (stat only)} & \\
\rho(770)^0 & 54 \pm 23 \text{ (stat only)} & & \\
\hline
\end{array}
\]

- Significant \(s\)-wave contribution with:
  - \(M(f_0(500)) = 0.856 \pm 0.086\) GeV/c\(^2\), \(\Gamma(f_0(500)) = 1.279 \pm 0.324\) GeV,
  - fraction of \(f_0(500)\) component of (27.7\pm3.1\)%.

- After efficiency correction:

\[
\begin{array}{|c|c|c|}
\hline
\text{Resonance} & \Upsilon(2S) \text{ corrected yield} & \Upsilon(3S) \text{ corrected yield} \\
\hline
S\text{-wave} & 541 \pm 65 \pm 53 & \\
f_2(1270) & 1043 \pm 78 \pm 36 & 285 \pm 26 \pm 15 \\
f_0(1710) & 95 \pm 32 \pm 24 & 22 \pm 29 \pm 11 \\
\hline
\end{array}
\]
$K^+K^-$ mass spectrum

- Summed over the $Y(2S)$ and $Y(3S)$ samples.
- Fit with mass function sum of (6 free parameters):
  - $f_0(980)$ described by Flatté formalism.
  - $f_2(1270)$, $f'_2(1525)$, $f_0(1500)$ (sum of both noted as $f_J(1500)$) and $f_0(1710)$ as relativistic Breit Wigner.
  - Combinatorial background.

<table>
<thead>
<tr>
<th>Resonance ($K^+K^-$)</th>
<th>Yield</th>
<th>$\Upsilon(2S) + \Upsilon(3S)$</th>
<th>Significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(980)$</td>
<td>$47 \pm 9$</td>
<td></td>
<td>5.6</td>
</tr>
<tr>
<td>$f_J(1500)$</td>
<td>$77 \pm 10 \pm 10$</td>
<td></td>
<td>8.9</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>$36 \pm 9 \pm 6$</td>
<td></td>
<td>4.7</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$15 \pm 8$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_0(2200)$</td>
<td>$38 \pm 8$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- After efficiency correction:

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\Upsilon(2S)/\Upsilon(3S)$ corrected yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_J(1500)$</td>
<td>$281 \pm 37 \pm 38$</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>$143 \pm 36 \pm 24$</td>
</tr>
</tbody>
</table>

[arXiv:1804.04044]
Legendre polynomial moments

- Information about the spin structure, and proportions of $S$ and $D$ wave amplitudes can be obtained from distributions of Legendre polynomial $Y_n^0$.

- In the case of the $K^+K^-$ spectrum, this partial wave analysis shows that the $f_J(1500)$ component is composed of both spin 0 and 2 resonances.

\[ \sqrt{4\pi} < Y_n^0 > = S^2 + D^2, \]
\[ \sqrt{4\pi} < Y_2^0 > = 2SD\cos\phi_{SD} + 0.639D^2, \]
\[ \sqrt{4\pi} < Y_4^0 > = 0.857D^2, \]
Helicity amplitude fits

- Complete spin-parity analysis is performed fitting the angular distributions expected for the various spin hypotheses, as a function of the decay angles in the Y(2/3S) decay chain, with unbinned likelihood fit in each resonance region.
  - $\theta_H$: helicity angle of $\pi$ or K,
  - $\theta_\gamma$: photon angle.
- Branching fractions extracted using fractions from these fits and the previous ones.

Spin 2:

$$W_2(\theta_\gamma, \theta_H) = \frac{dU(\theta_\gamma, \theta_H)}{d\cos\theta_\gamma d\cos\theta_H} = \frac{15}{1024} |E_{00}|^2 [9|A_{01}|^2 (22|C_{10}|^2 + 8|C_{11}|^2 + 9|C_{12}|^2) + 24 (|A_{01}|^2 (22|C_{10}|^2 + 24|C_{11}|^2 + 9|C_{12}|^2) + \sum \frac{24}{2} (|A_{01}|^2 + 3|A_{01}|^2) (2|C_{10}|^2 - 9|C_{11}|^2 + |C_{12}|^2) \cos 2\theta_H + 6 (|A_{01}|^2 (6|C_{10}|^2 - 8|C_{11}|^2 + |C_{12}|^2) + |A_{01}|^2 (18|C_{10}|^2 - 8|C_{11}|^2 + 3|C_{12}|^2)) \cos 4\theta_H - 2 (|A_{01}|^2 - |A_{01}|^2) \cos 2\theta_H + 12 (2|C_{10}|^2 - |C_{12}|^2) \cos 2\theta_H + 3 (6|C_{10}|^2 + 8|C_{11}|^2 + |C_{12}|^2) \cos 4\theta_H].$$

Spin 0:

$$W_0(\theta_\gamma) = \frac{dU(\theta_\gamma)}{d\cos\theta_\gamma} = \frac{3}{8} |C_{10}|^2 |E_{00}|^2 (|A_{00}|^2 + 3|A_{01}|^2 - (|A_{00}|^2 - |A_{01}|^2) \cos 2\theta_\gamma).$$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$B(10^{-5})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi \pi$ S-wave</td>
<td>$4.63 \pm 0.56 \pm 0.48$</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$10.15 \pm 0.59 \pm 0.43$</td>
</tr>
<tr>
<td>$f_0(1710) \rightarrow \pi \pi$</td>
<td>$0.79 \pm 0.26 \pm 0.17$</td>
</tr>
<tr>
<td>$f_1(1500) \rightarrow KK$</td>
<td>$3.97 \pm 0.52 \pm 0.55$</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>$2.13 \pm 0.28 \pm 0.72$</td>
</tr>
<tr>
<td>$f_0(1710) \rightarrow K\bar{K}$</td>
<td>$2.08 \pm 0.27 \pm 0.65$</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>$2.02 \pm 0.51 \pm 0.35$</td>
</tr>
</tbody>
</table>

Fit for spin 2 hypothesis, in $f_2(1270)$ region
Conclusions

• Dalitz plot analysis of $J/\psi$ decays with high statistics:
  • Provide complementary description of the resonance structures in the $J/\psi \rightarrow \pi^+ \pi^- \pi^0$ with Veneziano model.
  • First measurement of the $J/\psi \rightarrow K_s^0 K^+ \pi^-$.

• Studies of radiative $Y(1S)$ decays in $Y(1S) \rightarrow \pi^+ \pi^- \gamma$ and $Y(1S) \rightarrow K^+K^-\gamma$.
  • Spin-parity and branching fraction measurements.
  • Observation of the $f_0(1710)$ state in these decays, which can be used to gain information on glueball.