Search for a Stable Six-quark State in Upsilon Decays at BABAR

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On behalf of the BABAR collaboration
EPS conference, Ghent July 10-17, 2019
Introduction

- In the quark model, only mesons \((q\bar{q})\) and baryons \((qqq)\) are predicted
  - other states such as \((q\bar{q} q\bar{q})\), \((q\bar{q} qqq)(qq'q''qq'q'')\) are forbidden

- In recent years, however, several experiments found states consistent with tetraquarks \((q\bar{q} q\bar{q})\)
  - Belle: \(X(3872)\)
  - BES III: \(Z_c(3900)^+\)
  - BES III: \(Z_c(4430)^+\)
  …

- LHCb found pentaquarks:
  - \(P_c(4312), P_c(4440), P_c(4457)\)

Introduction

- So why not six-quark states?

- 1977 Jaffe proposed $H$-dibaryon: $S$-wave, flavor singlet state: $|udsuds\rangle$
  - a loosely bound $\Lambda\Lambda$ state
  - Bag model prediction: mass $m_H = 2150$ MeV

- If $m_H < 2m_\Lambda$, state is stable wrt strong decays
  $\Rightarrow$ $H$ is expected to decay weakly, lifetime $\sim 10^{-10}$ s

- Numerous searches for $H$-dibaryon did not find any state

Jaffe PRL 38, 195 (1977)


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In 2017, G. Farrar proposed a $|uuddss\rangle$ 6-quark state $S$ that is different from the loosely bound $H$-dibaryon state at 2150 MeV predicted by Jaffe.

- Charge: 0, baryon number: 2, strangeness: -2, scalar, $\gamma \rightarrow$ gluons $\rightarrow S\bar{\Lambda}\bar{\Lambda}$
- Very compact state: $r \sim 0.1$-0.4 fm $\Rightarrow$ recent Lattice QCD calculations indicate tightly bound $\Lambda\Lambda$ state
- Mass: $m_S < 2.0545$ GeV = $m_\Lambda + m_p + m_e$ $\Rightarrow$ if $m_S < 1.878$ GeV, $S$ is absolutely stable
- Flavor singlet $\Rightarrow$ allowed by QCD with small couplings to mesons

$S$-nucleon interactions are suppressed due to tiny wavefunction overlap $\Rightarrow$ neutron stars do not decay to $S$

$nn \rightarrow S\pi^0$ is not observed,

$S$ is not excluded by present experiments

Beanne et al, PRD 87, 034506 (2013)
Dark Matter Candidate

- The six-quark $S$ state could be the astronomical dark matter

- If dark matter (DM) consists of a nearly equal number of $u$, $d$, $s$ quarks, the formation rate is driven by a quark-gluon plasma transition to the hadronic phase ➔ DM models in this category include hexaquarks

- Hexaquark DM with a mass $\sim 1860$-$1880$ MeV can reproduce the ratio of DM to ordinary matter densities $\Omega_{DM}/\Omega_b$ within 15%

- In this scenario, the total baryon asymmetry in universe would be at a level close to the observed value after including the dark-matter contribution

- Note, that a low-mass hexaquark is hard to distinguish kinematically from a $n$
Search Strategy

- Look for $S$ or *hexaquark* in the process $\gamma(2S,3S) \rightarrow$ gluons $\rightarrow S\bar{\Lambda}\bar{\Lambda}$ or $\bar{S}\Lambda\Lambda$

- Perform blind analysis of $\gamma(2S,3S)$ data sets: $90 \times 10^6 \gamma(2S)$ decays and $110 \times 10^6 \gamma(3S)$ decays

- Use $\gamma(4S)$ data sets of $424.2 \text{ fb}^{-1}$ to evaluate off-peak background

- Fully reconstruct $\bar{\Lambda}\bar{\Lambda}$ or $\Lambda\Lambda$ in $p\pi$ decay ($B=0.64$) and calculate recoil mass

\[ m^2_{\text{rec}} = \left( p_T - p_{\bar{\Lambda}} - p_{\bar{\Lambda}} \right)^2 \]

- Distance of closest approach for $\Lambda$ is $> 5 \text{ cm}$

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Search Strategy

Event selection
- Require 4 charged tracks +1 additional track not from IR with DOCA>5 cm
- Apply loose PID criteria to select $p$ or $\bar{p}$
- Reconstruct $\bar{\Lambda}\bar{\Lambda}$ or $\Lambda\Lambda$ with $\Lambda \rightarrow p\pi^-$
- Require flight significance of each $\Lambda$: $|\vec{r}|/\sigma_r > 5$
- Require $\Lambda$ to point back to IR $\frac{\vec{r}_\Lambda \cdot \vec{p}_\Lambda}{|\vec{r}_\Lambda||\vec{p}_\Lambda|} > 0.9$

Signal: Examine extra neutral energy, $E_{\text{extra}}$ in region outside signal cone, i.e. the energy of all neutral clusters in EM calorimeter and require $E_{\text{extra}} < 500$ MeV

Use sample of $E_{\text{extra}} > 500$ MeV as validation sample
Sample after Preselection

- $E_{\text{extra}}$ distribution after preselection shows 92 events of which 8 events satisfy $E_{\text{extra}} < 500$ MeV

- $p\pi$ invariant mass shows true $\Lambda$ signal

- Kinematic fit of each $\Lambda$ to PDG mass and common production point in beam spot leaves 4 events

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Efficiency and Backgrounds

- Use dedicated signal MC
  - Generated with decay amplitude provided by Farrar
  - Generated with phase space (uniform)
  - Model S as a neutron or as neutrino (no interaction with detector material)

- Assess systematic errors from the different assumptions: $\sigma_{\text{tot}}=12.8\%-16.1\%$

- Efficiency including $B(\Lambda \to p\pi)^2$ varies from 7.2% at threshold to 8.2% near 2 GeV mainly driven by the geometric acceptance

- Resolution of the recoil mass is 100 MeV

- Background originates from $q\bar{q}$ continuum or $\gamma(2S, 3S)$ decays
  - Use $\gamma(4S)$ decays for $q\bar{q}$ continuum (signal is negligible)
  - Scale $\gamma(2S, 3S)$ MC so that MC+ $q\bar{q}$ continuum matches $E_{\text{extra}}$ sideband
  - Remaining background $\sim \Lambda\Lambda\,\bar{\Lambda}\bar{\Lambda}$ ($X$)

$\{n\pi^0, n\pi^0\}$ may pass or fail $E_{\text{extra}}$ selection

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Hexaquarks: Systematic Uncertainties

- Largest effects come from modeling production amplitude including angular distribution

- Assumption on S particle type

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>S angular distribution modeling</td>
<td>5-8%</td>
</tr>
<tr>
<td>S particle type modeling</td>
<td>8-11%</td>
</tr>
<tr>
<td>Λ reconstruction</td>
<td>4% per Λ</td>
</tr>
<tr>
<td>MC statistics</td>
<td>2%</td>
</tr>
<tr>
<td>Λ branching fraction</td>
<td>1.6%</td>
</tr>
<tr>
<td>Proton PID</td>
<td>1% per p</td>
</tr>
<tr>
<td>Number of Υ(2S, 3S)</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

Total systematic error: 12.8-16.1%

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Validation: $E_{\text{extra}} > 0.5$ GeV

In the $E_{\text{extra}}$ sideband we observe zero background events in the $m_{\text{rec}}^2$ signal region.

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Final results in the $E_{\text{extra}} < 500$ MeV region show no signal events for zero expected background.

Signal MC for $S$ with mass of 1.6 GeV and $\mathcal{B}(\Upsilon(nS) \to S\bar{A}A) = 10^{-7}$
Results

- We see no evidence for hexaquarks in the decay $\Upsilon(2S, 3S) \rightarrow S\bar{S}\bar{S}$

- We use the profile likelihood method to set branching fraction upper limits @ 90% confidence level in the mass range 0.0-2.05 GeV including systematic errors

- $\mathcal{B}(\Upsilon \rightarrow S\bar{S}\bar{S}) < (1.2-1.4) \times 10^{-7}$ @90% CL

- We could further look for $\Upsilon \rightarrow S\bar{S}\bar{S}X$
  - much harder analysis but may have branching fraction reachable with the BABAR sensitivity

PRL 122, 072002 (2019)

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Conclusions

- A tightly bound $S=|uuudss\rangle$ state may be more stable than previously predicted,
  - if $m_S < m_\Lambda + m_p + m_e = 2.0545$ GeV, it may be stable even on cosmological time scales
  - if it exists, it is a good candidate for dark matter
  - It is not excluded by searches for the H-dibaryon

- BABAR has searched for the $S$ in $\gamma(2S)$ and $\gamma(3S)$ decays in the recoil against $\bar{\Lambda}\bar{\Lambda}$ or $\Lambda\Lambda$ using a data sample of 200 million events

- No evidence for a stable hexaquark state is found in $\gamma(nS)$ decays and no background remains in signal region ➔ set stringent branching fraction upper limit:
  - $\mathcal{B}(\gamma \rightarrow S\bar{\Lambda}\bar{\Lambda}) < (1.2-1.4)\times10^{-7}$ @ 90% CL for $m<2.05$ GeV

- Need to extend searches to more inclusive channels like $S\bar{\Lambda}\bar{\Lambda}X$ since BABAR’s sensitivity for the exclusive channel $S\bar{\Lambda}\bar{\Lambda}$ may not be sufficient
Hexaquarks: Distance of Closest Approach

- Expected background distribution of DOCA of tracks not associated with a $\Lambda$ after application of all other selection criteria plus predicted signal distribution from MC
- The continuum background is evaluated from on-peak $\Upsilon(4S)$ data, signal MC is for $\Upsilon(2S, 3S)$
- Signal MC simulates hexaquark as $n$ or $\nu$
- # tracks not associated with a $\Lambda$ for DOCA > 5 cm and DOCA < 5 cm

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