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Search for a stable six-quark state in Υ decays at *BABAR*

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Recent investigations have suggested that the six-quark combination *uuddss* could be a deeply bound state (S) that has eluded detection so far, and a potential dark matter candidate. We report the first search for a stable, doubly strange six-quark state in $\Upsilon \to S\bar{\Lambda}\bar{\Lambda}$ decays with the *BABAR* experiment. No signal is observed, and limits on the combined $\Upsilon(2S,\ 3S) \to S\bar{\Lambda}\bar{\Lambda}$ branching fraction set stringent limits on the existence of such exotic particles.

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1. Introduction

In the traditional quark model, only mesons ($q\bar{q}$) and baryons (qqq) are predicted [1]. Other states such as ($q\bar{q}q\bar{q}$), ($q\bar{q}qq$), or ($qqqqqq$) were not considered since those were not observed. In recent years, however, several experiments found states consistent with tetraquarks ($q\bar{q}q\bar{q}$). For example, the Belle experiment first observed the $X(3872)$, a $J^{PC} = 1^{++}$ state in $B \to K\pi^+\pi^- J/\psi(1S)$ [2]. Figure 1 (left) shows the $J/\psi\pi^+\pi^-$ invariant-mass spectrum, which reveals a prominent peak at 3872 MeV/c^2. The state has exotic properties that differ from a conventional $q\bar{q}$ state. The classification as a tetraquark state is the most likely option. The BES III experiment first observed the $Z_c(3900)^+$ state [3] and Belle first observed the $Z_c(4430)^+$ state, which have properties that are incompatible with a $q\bar{q}$ assignment. These states are consistent with being tetraquark states as well. By now, the LHCb experiment observed three pentaquark states, the $P_c(4312)$, the $P_c(4440)$ and the $P_c(4457)$ [5]. They are visible in the $J/\psi p$ invariant-mass spectrum displayed in Fig. 1 (right). Therefore, it is rather likely that also six-quark states may exist.

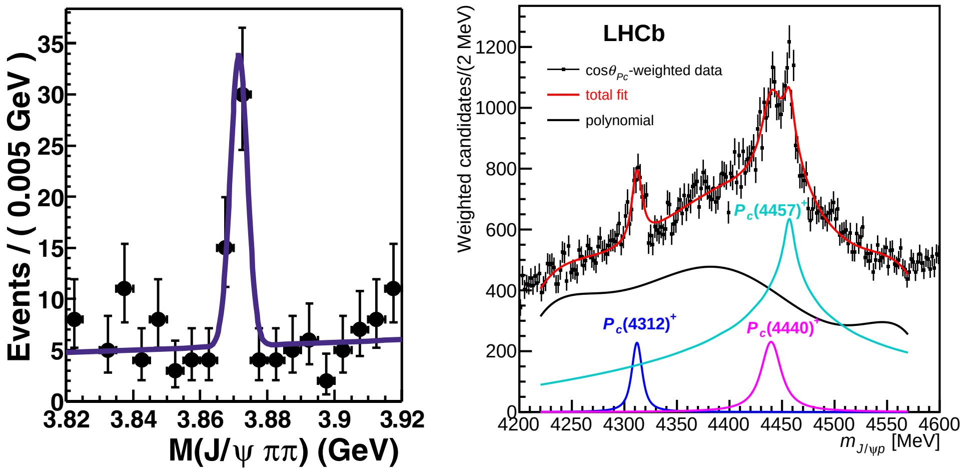

Figure 1: Left: The $J/\psi\pi^+\pi^-$ invariant-mass spectrum observed by Belle showing the $X(3872)$ exotic state. Right: The $J/\psi p$ invariant-mass spectrum from LHCb showing three pentaquark states, the $P_c(4412)^+$, $P_c(4440)$ and $P_c(4457)$ states [5].

In 1977, Jaffe proposed the H-dibaryon, a $|udsuds\rangle$, S-wave and flavor singlet state that is a loosely bound $\Lambda\Lambda$ state [7]. The bag model predicted its mass to be $m_H = 2150$ MeV/c^2. If $m_H < 2m_\Lambda$ the state is stable with respect to strong decays. Therefore, the H is expected to decay weakly, with a lifetime of 10^{-10} s. Numerous searches for an H-dibaryon, however, did not find any signal.

In 2017, Farrar proposed a $|uuddss\rangle$ six-quark state S that is different from the loosely bound H-dibaryon state at 2150 MeV predicted by Jaffe. The scalar state has charge zero, baryon number two, strangeness minus two, and should be produced in decays such as $\Upsilon \to gluons \to S\bar{\Lambda}\bar{\Lambda}$ [9]. It is a very compact state with a radius of $0.1-0.4$ fm. Recent Lattice QCD calculations indicate that it is a tightly bound $\Lambda\Lambda$ state with a mass $m_S < m_\Lambda + m_p + m_e = 2.0545$ GeV/c^2. if $m_S < 1.878$ GeV/c^2, S is absolutely stable. It is a flavor singlet that is allowed by QCD with small couplings to mesons. Figure 2 shows the binding energy of various di-baryon systems calculated in lattice gauge theories [10]. Note that the singlet state is the most stable di-baryon state. The

S-nucleon interactions are suppressed due to the tiny wave function overlap. Thus, neutron stars do not decay to S. Also, the decay $nn \to S\pi^0$ is not observed, Searches of past experiments rule out $m_S > 2~\mathrm{GeV/c^2}$. However, the mass region below $2~\mathrm{GeV/c^2}$ have not been explored.

The six-quark S state could be the astronomical dark matter (DM). If dark matter 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. So DM models in this category include hexaquarks. Please note that hexaquark DM with a mass of 1860-1880 $\mathrm{MeV/c^2}$ can reproduce the ratio of DM to ordinary matter densities Ω_{DM}/Ω_b within 15%. In this scenario, the total baryon asymmetry in the universe would be at a level close to the observed value after including the dark-matter contribution. Please also note that a low-mass hexaquark is hard to distinguish kinematically from a neutron.

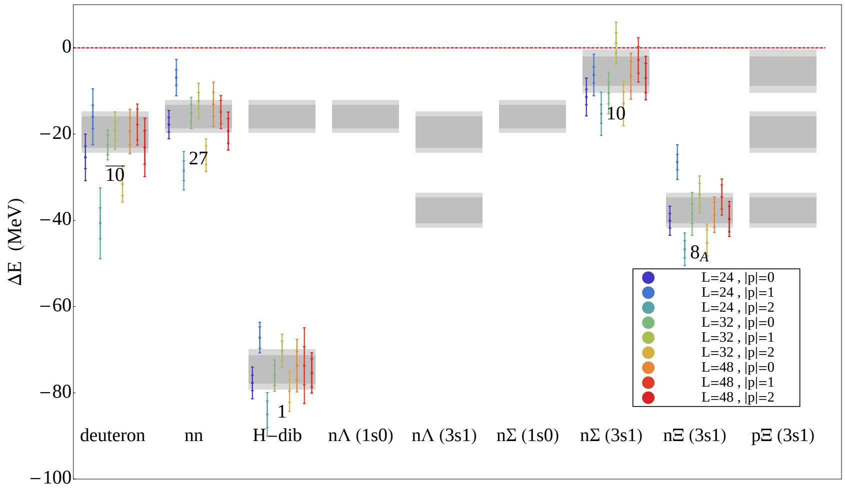

Figure 2: Binding energies of two-baryon systems calculated in lattice QCD. The grey-shaded regions denote statistical uncertainties while the colored error bars show statistical and systematic errors combined. The different colors show results for three lattice dimensions and different momenta [10].

2. Search Strategy

The *BABAR* experiment has searched for the hexaquark S in the process $\Upsilon(2S,\,3S) \to gluons \to S\bar{\Lambda}\bar{\Lambda}$ or $\bar{S}\Lambda\Lambda$ performing a blind analysis of 90×10^6 $\Upsilon(2S)$ decays and 100×10^6 $\Upsilon(3S)$ decays. The $\Upsilon(4S)$ data set of 424.2 $\mathrm{fb^{-1}}$ is used to evaluate the off-peak background since according to simulations the contribution of B meson decays to the final mass spectrum is negligible. The $\bar{\Lambda}\bar{\Lambda}$ ($\Lambda\Lambda$) system is fully reconstructed in the $\bar{p}\pi^+\bar{p}\pi^+$ ($p\pi^-p\pi^-$) decays. The $\Lambda \to p\pi^-$ decay has a branching fraction of $\mathscr{B}(\Lambda \to p\pi^-) = 0.64$. With the fully reconstructed $\bar{\Lambda}$s the recoil mass $m^2_{rec} = (p_\Upsilon - p_{\bar{\Lambda}} - p_{\bar{\Lambda}})^2$ is calculated. Figure 3 (left) shows the topology of the process $e^+e^- \to \Upsilon(2S,\,3S) \to gluons \to S\bar{\Lambda}\bar{\Lambda}$. The S lies in the recoil of the $\bar{\Lambda}\bar{\Lambda}$ system.

We select events that have four charged tracks. One additional track is allowed that does not come from the interaction region having a distance of closest approach $DOCA > 5$ cm. This accounts for particles that are produced in secondary interactions with the detector material. We apply loose particle identification criteria to select p or $\bar{p}$. We reconstruct $\bar{\Lambda}\bar{\Lambda}$ or $\Lambda\Lambda$ using the $\bar{p}\pi^+$ or $p\pi^-$ decay. For each $\bar{\Lambda}(\Lambda)$ we require a flight distance significance of $|\vec{r}_\Lambda|/\sigma_{r_\Lambda} > 5$ where r_Λ is the flight distance vector. The $\bar{\Lambda}(\Lambda)$ have to point back to interaction region, $\vec{r}_\Lambda \cdot \vec{p}_\Lambda/(|\vec{r}_\Lambda||\vec{p}_\Lambda|) > 0.9$. To extract the signal we examine the extra neutral energy E_{extra}, which is the energy of all neutral clusters in electromagnetic calorimeter except for a cone around the S. Figure 3 (right) shows an event display of a simulated signal event. The pink cone shows the region that is not included in the determination of E_{extra}. For signal we require $E_{extra} < 500$ MeV. We use the sample $E_{extra} > 500$ MeV for validation.

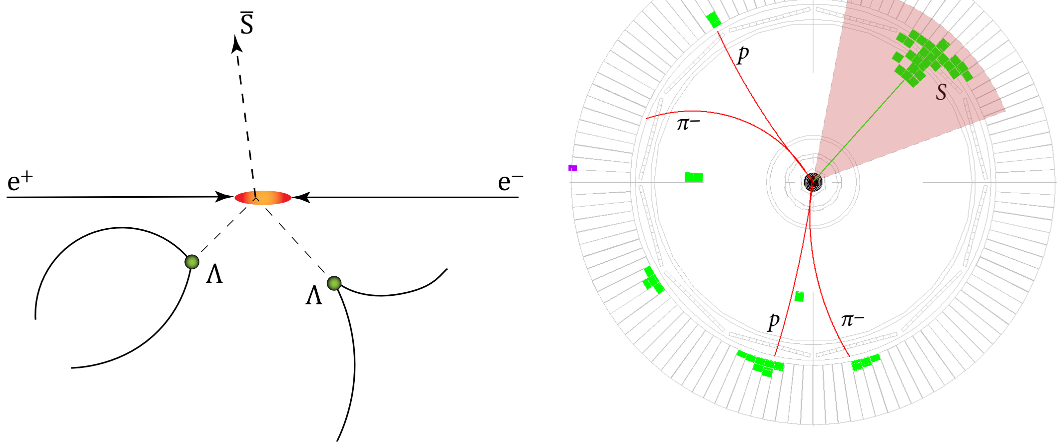

Figure 3: Left: Topology of the process $e^+e^- \to \Upsilon(2S,\ 3S) \to gluons \to S\bar{\Lambda}\bar{\Lambda}$. Right: Event display of a simulated signal event. Clusters lying in the pink cone are not included in the E_{extra} calculation.

Figure 4 (left) shows the E_{extra} distribution after preselection. We see 92 events of which 8 events satisfy $E_{extra} < 500$ MeV. The $p\pi$ invariant mass shows a true Λ signal as depicted in Fig. 4 (right). After performing a kinematic fit of each Λ candidate by constraining the mass to the nominal Λ mass and requiring a common point in the beam spot leaves four candidates.

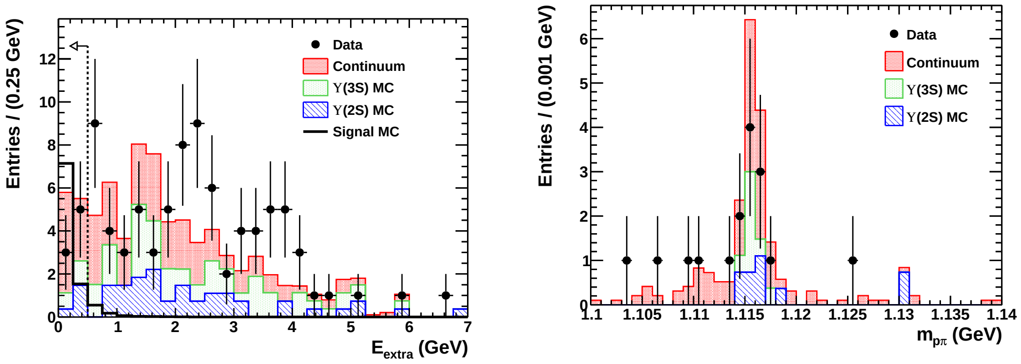

Figure 4: Left: The distribution of extra energy in the calorimeter E_{extra} after preselection. Right: The $p\pi$ invariant mass of all candidates that satisfy $E_{extra} < 500\ \text{MeV}/\text{c}^2$.

Table 1: Systematic uncertainties.

Source	Systematic error
S angular distribution modeling	$5-8\%$
S particle type modeling	$8-11\%$
Λ reconstruction	4% per Λ
Monte Carlo statistics	2%
Λ branching fraction	1.6%
proton particle identification	1% per p
Number of $\Upsilon(2S,\ 3S)$	0.6%

3. Efficiency and Backgrounds

For simulation of the signal we use dedicated signal Monte Carlo samples that were generated both with the decay amplitude provided by Farrar [11] and with phase space. We model the hexaquark S as a neutron or as a neutrino that has no interaction with the detector material. The efficiency including $\mathscr{B}(\lambda \to p\pi^-)^2$ varies from 7.2% at threshold to 8.2% near 2 GeV/c^2 and is mainly driven by the geometric acceptance. The resolution of the recoil mass is 100 MeV/c^2. The background originates from $q\bar{q}$ continuum with $q = u,\ d,\ s,\ c$ or from $\Upsilon(2S)$ and $\Upsilon(3S)$ decays. We use $\Upsilon(4S)$ decays for $q\bar{q}$ continuum determination since the signal contribution is negligible. We scale the $\Upsilon(2S)$ and $\Upsilon(3S)$ Monte Carlo samples so that the Monte Carlo and $q\bar{q}$ continuum matches the E_{extra} sideband. A residual background consists of $\bar{\Lambda}\bar{\Lambda}(\Lambda\Lambda)X$ events in which the $\bar{\Lambda}(\Lambda)$ decays to $\bar{n}(n)\pi^0$. This background may pass or fail the E_{extra} selection.

4. Systematic Uncertainties

Table 1 summarizes the different types of systematic uncertainties. The largest effects come from modeling the hexaquark production amplitude and the angular distribution. The total systematic error ranges from 12.8% to 16.1%.

5. Validation and Results

Figure 5 (left) shows the distribution of the recoil mass m_{rec} squared for the validation sample for which $E_{extra} > 500$ MeV/c^2. In the E_{extra} sideband we observe zero background events in the m_{rec} signal region. Figure 5 (right) shows m_{rec} squared for $E_{extra} < 500$ MeV/c^2 in which we see no events in the signal region. The four candidates populate the high mass region. To illustrate how a signal would look like, we performed a simulation of S with a mass of 1.6 GeV/c^2 and a branching fraction of $\mathscr{B}(\Upsilon(nS) \to S\bar{\Lambda}\bar{\Lambda}) = 10^{-7}$. We see no evidence for hexaquarks in the decays $\Upsilon(2S,\ 3S) \to S\bar{\Lambda}\bar{\Lambda}$. We use the profile likelihood method to set branching fraction upper limits at 90% confidence level in the mass range 0.0-2.05 GeV including systematic errors. Figure 6 shows the branching fraction upper limits at 90% confidence level as a function of the S mass. The upper limit on the branching fraction at 90% confidence level is $\mathscr{B}(\Upsilon \to S\bar{\Lambda}\bar{\Lambda}) < 1.4 \times 10^{-7}$ at low masses falling off to $\mathscr{B}(\Upsilon \to S\bar{\Lambda}\bar{\Lambda}) < 1.2 \times 10^{-7}$ at high masses.

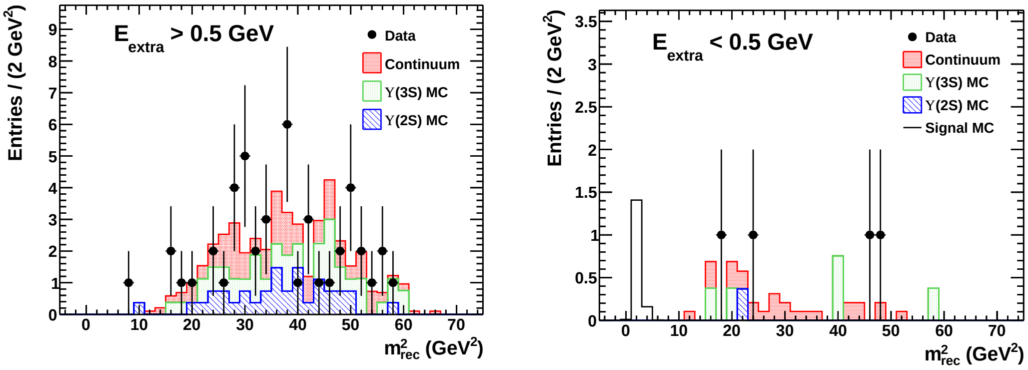

Figure 5: Left: Distribution of the recoil mass for all candidate with $E_{extra} > 500$ MeV$/c^2$. Right: Distribution of the recoil mass for signal candidate with $E_{extra} < 500$MeV$/c^2$.

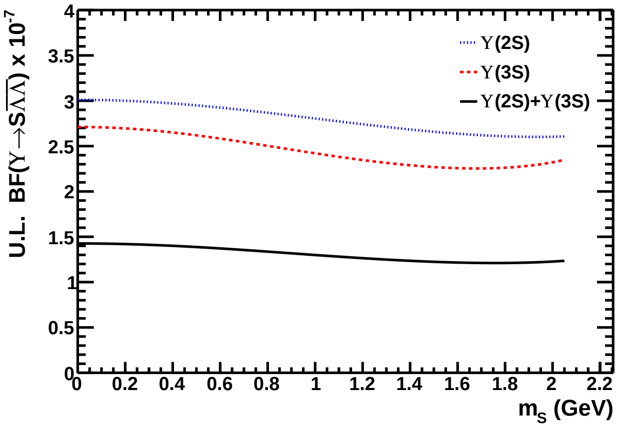

Figure 6: Branching fraction upper limits at 90% confidence level as a function of m_S for $\Upsilon(2S) \to S\bar{\Lambda}\bar{\Lambda}$ (blue dotted curve), for $\Upsilon(3S) \to S\bar{\Lambda}\bar{\Lambda}$ (red dashed curve) and for both samples combined (black solid line).

6. Conclusion

A tightly bound $S = |uudds\rangle$ state may be more stable than previously predicted. If $m_S < m_\Lambda + m_p + m_e = 2.0545$ GeV$/c^2$, 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 hexaquark S in $\Upsilon(2S)$ and $\Upsilon(3S)$ decays in the recoil against $\bar{\Lambda}\bar{\Lambda}$ using a data sample of 200 million $\Upsilon(2S)$ and $\Upsilon(3S)$ events. No evidence is found in $\Upsilon(nS)$ decays for a stable hexaquark state. We see no background events in the signal region and set a stringent branching fraction upper limit of $\mathscr{B}(\Upsilon \to S\bar{\Lambda}\bar{\Lambda}) < (1.2-1.4)\times 10^{-7}$ at 90% confidence level for $m_S < 2.05$ GeV.

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