Search for Dark Matter in Upsilon Decays at BABAR Experiment

Romulus Godang
Department of Physics, University of South Alabama, 411 University Boulevard, North, Mobile AL 36688, U.S.A.
E-mail: godang@southalabama.edu

Abstract. Recent investigations have suggested that the singlet six-quark combination uuddss may be a deeply bound state $S$, called Sexaquark. An essentially stable state $S$ is a potentially excellent Dark Matter candidate. We present the first search for a stable, doubly strange six-quark state in the decays of $\Upsilon(4S) \rightarrow \Lambda\bar{\Lambda}$. Based on a data sample of $\Upsilon(2S)$ and $\Upsilon(3S)$ decays collected by the BABAR Experiment we report the most recent results and set stringent limits on the existence of such exotic particle.

1. Introduction
A hexa-quark di-baryon uuddss or $S$ could be a Dark Matter candidate within the Standard Model [1, 2, 3]. A large binding energy might make $S$ to be light enough that is stable or long lived. The spatial wavefunction of the $S$ is completely symmetric that imply that it should be the most tightly bound six-quark state of its class [4], at the same time the color, spin wavefunctions and flavor are totally asymmetric. The $S$ is a spin 0, flavor-singlet and parity-even boson with $Q=0$, $B=2$, and $S=-2$.

The $S$ is absolutely stable if its mass, $m_S$, is lighter than $2(m_p + m_e) = 1877.6$ MeV. If its mass $m_S < m_p + m_e + m_\Lambda = 2054.5$ MeV, it decays via a doubly-weak interaction and its lifetime could be very long. A stable $S$ is allowed by Quantum Chromodynamics (QCD) and would have eluded detection in both accelerator and non-accelerator experiments. So far such as bound state $S$ has not been excluded by hypernuclei decays and direct searches for long-lived neutral state. The stable $S$ has not been detected so far. It is difficult to distinguish the $S$ kinematically from the neutron that attributes might explain why this state has escaped detector. The $S$ does not couple to photon, pions, and most of other mesons because of its charge neutral and it has a flavor-singlet. The $S$ is probably more compact than the ordinary baryons.

2. The BABAR Detector
The BABAR detector was operated at the PEP-II asymmetric-energy storage rings at the SLAC National Accelerator Laboratory. We analyze the data recorded with the BABAR detector about 28 fb$^{-1}$ data at $\Upsilon(3S)$ and 14 fb$^{-1}$ data at $\Upsilon(2S)$ [5]. Additional samples of an integrated luminosity of 428 fb$^{-1}$ collected at $\Upsilon(4S)$ at a center of mass energy of 10.58 GeV are used to estimate the background.

A detail description of the BABAR detector is presented elsewhere [6, 7]. The momenta of the charged particles are measured in a tracking system consisting of a 5-layer double sided
silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). The SVT and DCH operate within a 1.5 T solenoid field and have a combined solid angle coverage in the center of mass frame of 90.5%. A detector of internally reflected Cerenkov radiation (DIRC) is used for charged particle identifications of pions, kaons, and protons with likelihood ratios calculated from $dE/dx$ measurements in the SVT and DCH. Photons and long-lived neutral hadrons are detected and their energies are measured in a CsI(Tl) electromagnetic calorimeter (EMC). For electrons, energy lost due to bremsstrahlung is recovered from deposits in the EMC.

3. Stable Six-Quark State

We searched the exclusive decay of $\Upsilon(2S,3S) \rightarrow S\bar{\Lambda}\bar{\Lambda}$. The inclusive six-quark production in the $\Upsilon(1S,2S,3S)$ decays is predicted at the level of $10^{-7}$ with significant uncertainties. Inclusion of the charged conjugate mode is implied throughout this analysis. The exclusive decays of $\Upsilon \rightarrow S\bar{\Lambda}\bar{\Lambda}$ or $S\Lambda\Lambda + \pi$ and/or $\gamma$ are ideal discovery channels proposed by Farrar [2]. No specific prediction of the branching fraction of the decay $\Upsilon(2S,3S) \rightarrow S\bar{\Lambda}\bar{\Lambda}$.

The $S$ angular distribution is simulated using an effective Lagrangian based on a constant matrix element by assuming that angular momentum suppression effects are small [8]. The interaction between six-quark states and matter is simulated to be similar to that of neutrons. The $\Upsilon(2S,3S,4S)$ decays events are generated using EvtGen [9]. The detector acceptance and reconstruction efficiency are determined using Monte Carlo (MC) simulation based on GEANT4 [10].

The events containing at most five tracks and two $\Lambda$ candidates with the same strangeness, consistent with the topology of the process: $e^+e^- \rightarrow S\bar{\Lambda}\bar{\Lambda}$ final state are selected. The events are reconstructed in the $\Lambda\Lambda \rightarrow p\pi^- p\pi^-$ final state by requiring $1.10 \text{ GeV} < m_{\pi}\pi < 1.14 \text{ GeV}$. The additional track not associated with any $\Lambda$ candidate with a distance of closest approach (DOCA) from the primary interaction larger than 5 cm is selected. The protons and anti-protons are selected by particle identification (PID) algorithms. The PID requirement is approximately 95% efficient for identifying protons and anti-protons and removes a large amount of four-pion final state background. The total energy clusters in the electromagnetic calorimeter not associated with charged particles, $E_{\text{extra}}$, must be less than 0.5 GeV. To reduce the contribution of cluster fragments, the distance between the cluster and the proton is required to be greater than 40 cm. Figure 1 shows the $E_{\text{extra}}$ distribution after applying all other selection criteria.

To maximize the signal sensitivity the selection procedure is tuned by taking into account the systematic uncertainties that are related to $S$ production and the interaction with detector materials. After applying these criteria the $p\pi^-$ mass distribution is shown in Fig 2. A total of eight of $\Upsilon \rightarrow S\bar{\Lambda}\bar{\Lambda}$ candidates are selected.

We then fit the events by imposing a mass constraint to each $\Lambda$ candidate and requiring a common production of the beam interaction point. We select combination with $\chi^2 < 25$, for 8 d.o.f, retaining four signal candidates. The signal is identified as a peak in the recoil mass squared, $m_{\text{rec}}^2$, in the region $0 \text{ GeV}^2 < m_{\text{rec}}^2 < 5 \text{ GeV}^2$. The recoil mass squared, $m_{\text{rec}}^2$ distribution is shown in Fig 3.

No significant signal is observed and we derive 90% confidence level (C.L.) upper limits on the $\Upsilon(2S,3S) \rightarrow S\bar{\Lambda}\bar{\Lambda}$ branching fractions, scanning $S$ masses in the range $0 \text{ GeV} < m_S < 2.05 \text{ GeV}$ in steps of 50 MeV. For each mass hypothesis, we evaluate the upper bound from the $m_{\text{rec}}^2$ distribution with a profile likelihood method [11].

The main uncertainties on the efficiencies arise from the modeling of the angular distribution of the $\Upsilon(2S,3S) \rightarrow S\bar{\Lambda}\bar{\Lambda}$ to be about 4% and it rises to 15%. The systematic uncertainty due to the limited knowledge of the interactions between the six-quark state with matter is estimated from 8% to 10%. The systematic uncertainty due to the difference in $\Lambda$ reconstruction efficiencies between data and MC calculations is 8%. The systematic uncertainty on the $\Lambda \rightarrow p\pi$ branching fraction to be 1.6% and due to the finite MC sample is 1.5%.
3

Figure 1. The distribution of the extra neutral energy ($E_{\text{extra}}$), before performing the kinematic fit for $\Upsilon(3S)$ and $\Upsilon(2S)$, and various background estimates: continuum (red), $\Upsilon(3S)$ MC (green), $\Upsilon(2S)$ MC (blue), and signal MC (solid line).

Figure 2. The distribution of the $p\pi$ invariant mass, $m_{p\pi}$, before performing the kinematic fit for $\Upsilon(3S)$ and $\Upsilon(2S)$, and various background estimates: continuum (red), $\Upsilon(3S)$ MC (green), and $\Upsilon(2S)$ MC (blue).

4. Conclusion
We have performed the first search for a stable six-quark state, uuddss configuration in the $\Upsilon(2S)$ and $\Upsilon(3S)$ decays. No signal is observed and we derive 90% confidence level (C.L.) upper limits on the branching fraction of the $\Upsilon(2S, 3S) \rightarrow S \bar{A} \bar{A}$ to be $(1.2 - 1.4) \times 10^{-7}$ [12]. These results set stringent bounds on the existence of a stable six-quark state.

5. Acknowledgments
The author would like to thank the organizers of the 16th International Conference on Topics in Astroparticle and Underground Physics in Toyama, Japan. The supports from the BABAR Collaboration and the University of South Alabama are gratefully acknowledged.
Figure 3. The distribution of the recoil mass squared, $m_{rec}^2$, against the $\Lambda\Lambda$ system, after applying the kinematic fit with various background estimates for the $E_{extra} < 0.5$ GeV signal region.

Figure 4. The 90% C.L. upper limits on the $\Upsilon(2S,3S) \rightarrow S\bar{\Lambda}\bar{\Lambda}$ branching fractions and the combined of $\Upsilon(2S)$ and $\Upsilon(3S)$.

References
[1] G. R. Farrar, G. Zaharijas, Phys. Rev. D 37, 014008 (2004).
[2] G. R. Farrar, arXiv: 1708.08951 (2017).
[3] G. R. Farrar, arXiv: 1711.10971 (2017).
[4] J. Preskill, Nucl. Phys. B 177, 21, (1981).
[5] J. P. Lees et al. (BABAR Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 726, 203 (2013).
[6] B. Aubert et al., (BABAR Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 729, 1 (2013).
[7] B. Aubert et al. (BABAR Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 1 (2002).
[8] G. R. Farrar (private communication).
[9] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A 462, 152 (2001).
[10] S. Agostinelli et al. (GEANT4 Collaboration), Nucl. Instrum. Meth. A 506, 250 (2003).
[11] W. A. Rolke, A. M. Lopez and J. Conrad, Nucl. Instrum. Meth. A 551, 493 (2005).
[12] J. P. Lees et al. (BABAR Collaboration), Phys. Rev. Lett. 122, 072002 (2019).