Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Yong-Feng Liu and Xian-Wei Kang 2016 *J. Phys.: Conf. Ser.* **738** 012043

Journal of Physics: Conference Series **738** (2016) 012043 doi:10.1088/1742-6596/738/1/012043

Test baryon antibaryon oscillation in collider experiments

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Abstract. Searching for the New Physics (NP) phenomenon beyond Standard Model (SM) is still a main focus in particle physics. Here we propose to search for $\Lambda - \overline{\Lambda}$ oscillation in the decay $J/\psi \to \Lambda\bar{\Lambda}$ using BES detector. With one-year luminosity at BESIII, we can put a constraint that the $\Lambda - \overline{\Lambda}$ oscillation mass is smaller than 10^{-15} MeV at 90% confidence level, corresponding to the oscillation time of 10^{-6} second around, in case of non-observation of any signals. These measurements should provide very precious informations besides the neutron oscillation experiment. Also it would be the first-time access by experiment for $\Lambda - \overline{\Lambda}$ oscillation.

1. Introduction

Standard Model (SM) has becomes a fundamental theory in particle physics, but the efforts for searching for the New Physics (NP) phenomenon beyond SM never desists. The baryon-number-violating process that is prohibited by SM is one of the main directions, which is also related to the more basic question of understanding the baryon asymmetry in the universe, according to the Sakharov conditions [1]: Baryon number B violation; C symmetry and CP-symmetry violation; Interactions out of thermal equilibrium. We notice that the standard $D^0\overline{D}^0$ mixing technique can be extended to the Λ baryon sector, if the $\Lambda - \overline{\Lambda}$ oscillation indeed exists. Then we discuss its feasibility in collider experiments.

2. Formalism

We will fully follow the convention that is used in the neutral D and B meson mixing, see Ref. [2, 3, 4] for a more comprehensive details. However, note here we are discussing the $\Lambda - \overline{\Lambda}$ oscillation, which is a $\Delta B = 2$ process, and thus certainly a NP phenomenon. We sketch our main idea, and the technical details can be found in Refs. [5, 6].

For the $\Lambda - \overline{\Lambda}$ system, we can write a Schrödinger-like equation as

$$i\frac{\partial}{\partial t}\begin{pmatrix} \Lambda(t) \\ \overline{\Lambda}(t) \end{pmatrix} = \mathbf{M}\begin{pmatrix} \Lambda(t) \\ \overline{\Lambda}(t) \end{pmatrix}, \tag{1}$$

where $\mathbf{M}$ matrix plays the role of Hamiltonien and

$$\mathbf{M} = \begin{pmatrix} m_\Lambda - \Delta E_\Lambda & \delta m_{\Lambda\overline{\Lambda}} \\ \delta m_{\Lambda\overline{\Lambda}} & m_{\overline{\Lambda}} - \Delta E_{\overline{\Lambda}} \end{pmatrix}, \tag{2}$$

Journal of Physics: Conference Series **738** (2016) 012043 doi:10.1088/1742-6596/738/1/012043

where m is the mass of Λ (or $\overline{\Lambda}$); δm is the oscillation mass, or can be understood as a coupling between Λ and $\overline{\Lambda}$ indicating the strength of the oscillation. Note the identical off-diagonal element due to the CPT invariance. ΔE is an external energy, and will be zero in the case of absence of the external field. In case of a magnetic field, $\Delta E_\Lambda = -\vec{\mu}_\Lambda \cdot \vec{B}$ and $\Delta E_{\overline{\Lambda}} = -\vec{\mu}_{\overline{\Lambda}} \cdot \vec{B}$ with $\vec{\mu}$ the magnetic moment. The minus sign in $m - \Delta E$ in the diagonal element is puly a convention, and writing as $+$ corresponds to exchange of the role of Λ and $\overline{\Lambda}$. Considering $\Lambda - \overline{\Lambda}$ oscillation, one can write the eigenstates as

$$
\begin{aligned}
|\Lambda_H\rangle &= \frac{1}{\sqrt{2}}(\sqrt{1+z}|\Lambda\rangle + \sqrt{1-z}|\overline{\Lambda}\rangle), \\
|\Lambda_L\rangle &= \frac{1}{\sqrt{2}}(\sqrt{1-z}|\Lambda\rangle - \sqrt{1+z}|\overline{\Lambda}\rangle)\,,
\end{aligned} \tag{3}
$$

with $z \equiv \frac{2\Delta E}{\Delta m}$; $\Delta E \equiv |\Delta E_\Lambda| = |\Delta E_{\overline{\Lambda}}|$ and $\Delta m \equiv m_H - m_L = 2\sqrt{(\Delta E)^2 + \delta m^2_{\Lambda\overline{\Lambda}}}$, i.e., the mass difference between heavy and light Λ. It turns out that the probability of finding a $\overline{\Lambda}$ in a beam of Λ after time t is described by [7]

$$
\mathcal{P}(\overline{\Lambda}, t) = \frac{\delta m^2_{\Lambda\overline{\Lambda}}}{\delta m^2_{\Lambda\overline{\Lambda}} + (\Delta E)^2} \sin^2(\sqrt{\delta m^2_{\Lambda\overline{\Lambda}} + (\Delta E)^2} \cdot t). \tag{4}
$$

For free Λ in absence of external field, $\Delta E = 0$, and Eq. (4) becomes

$$
\begin{aligned}
\mathcal{P}(\overline{\Lambda}, t) &= \sin^2(\delta m_{\Lambda\overline{\Lambda}} \cdot t) \\
&\approx (\delta m_{\Lambda\overline{\Lambda}} \cdot t) = \left(\frac{t}{\tau_{\Lambda\overline{\Lambda}}}\right)^2,
\end{aligned} \tag{5}
$$

where we have defined the relation between oscillation mass and oscillation time. A derivation with more details can be found in Appendix A in Ref. [8]. The recent status of the study of the neutron anti-neutron oscillation is summarized in Ref. [9]. Hereafter, we consider the possible search of $\Lambda - \overline{\Lambda}$ oscillation in $J/\psi \to \Lambda\overline{\Lambda}$ coherent decay. Here "coherent" means the $\Lambda\overline{\Lambda}$ should occur in $C = -1$, with C the charge parity. We take the results from PDG for the $D^0 - \overline{D}^0$ mixing [2], i.e., the general expression for the time-dependent decay rate is

$$
\begin{aligned}
R(f_1, f_2; t) &\equiv \frac{d\Gamma(J/\psi \to \Lambda_{\text{phys}}\overline{\Lambda}_{\text{phys}} \to f_1 f_2)}{dt} \\
&= \frac{1}{4}\mathcal{N}e^{-\Gamma|t|}\Big[(|a_1|^2 + |a_2|^2)\cosh(y_\Lambda \Gamma t) + (|a_1|^2 - |a_2|^2)\cos(x_\Lambda \Gamma t) \\
&\quad + 2\mathcal{R}e(a_1 a_2^*)\sinh(y_\Lambda \Gamma t) + 2\mathcal{I}m(a_1 a_2^*)\sin(x_\Lambda \Gamma t)\Big],
\end{aligned} \tag{6}
$$

where $\mathcal{N}$ is a common normalization factor and will be cancelled in the following observables. In Eq. (6), terms proportional to $|a_1|^2$ are associated with decays that occur without any net oscillation, while terms proportional to $|a_2|^2$ indeed follow from a net oscillation. The other terms are their interference. The mixing parameters are defined as

$$
\begin{aligned}
m &\equiv \frac{m_H + m_L}{2}, \quad \Delta m \equiv m_H - m_L\,, \\
\Gamma &\equiv \frac{\Gamma_H + \Gamma_L}{2}, \quad \Delta\Gamma \equiv \Gamma_H - \Gamma_L\,, \\
x_\Lambda &\equiv \frac{\Delta m}{\Gamma}, \qquad y_\Lambda \equiv \frac{\Delta\Gamma}{2\Gamma}.
\end{aligned} \tag{7}
$$

The time-integrated quantity $R(f_1, f_2)$ can then be expressed as

$$R(f_1, f_2) = \frac{1}{4}\mathcal{N}\left[(|a_1|^2 + |a_2|^2)\frac{1}{1-y_\Lambda^2} + (|a_1|^2 - |a_2|^2)\frac{1}{1+x_\Lambda^2}\right]. \tag{8}$$

Note that t is the time difference between Λ and $\overline{\Lambda}$ and should be integrated from $-\infty$ to ∞. The quantities a_1 and a_2 are

$$\begin{aligned} a_1 &\equiv A_{f_1}\overline{A}_{f_2} - \overline{A}_{f_1}A_{f_2} \\ a_2 &\equiv z(A_{f_1}\overline{A}_{f_2} + \overline{A}_{f_1}A_{f_2}) - \sqrt{1-z^2}(A_{f_1}A_{f_2} - \overline{A}_{f_1}\overline{A}_{f_2}) \end{aligned} \tag{9}$$

with $A_{f_i} \equiv \langle f_i|\mathcal{H}|\Lambda\rangle$, $\overline{A}_{f_i} \equiv \langle f_i|\mathcal{H}|\overline{\Lambda}\rangle$ $(i = 1, 2)$.

In what follows, we will discuss two separate cases: i) in the external field such that $z \to 1$ ii) in the absence of the external field, then $z = 0$.

- z=1
  At BES-III, the external magnetic field is about 1.0 T, and then $\Delta E \sim 2\times 10^{-11}$ MeV, $z \to 1$. For $f_1 = f_2 = p\pi^-$

$$R(p\pi^-, p\pi^-; t) = \mathcal{N}e^{-\Gamma|t|}|A_{p\pi^-}|^2|\overline{A}_{p\pi^-}|^2\frac{x_\Lambda^2 + y_\Lambda^2}{2}(\Gamma t)^2, \tag{10}$$

  where we have neglected CP violation and expanded the terms up to order of x_Λ^2 or y_Λ^2. Similarly,

$$R(p\pi^-, \overline{p}\pi^+; t) = \mathcal{N}\frac{1}{2}e^{-\Gamma|t|}|A_{p\pi^-}|^2|\overline{A}_{\overline{p}\pi^+}|^2. \tag{11}$$

  where since this mode is a favourable one and we keep only the leading term. The ratio of Eq. (10) to Eq. (11) is

$$\mathcal{R}(t) = 2|\lambda_{p\pi^-}|^2\frac{x_\Lambda^2 + y_\Lambda^2}{2}(\Gamma t)^2, \quad \lambda_{p\pi^-} = \frac{\overline{A}_{p\pi^-}}{A_{p\pi^-}} \tag{12}$$

  and the time-integrated case reads

$$\mathcal{R} = 2|\lambda_{p\pi^-}|^2(x_\Lambda^2 + y_\Lambda^2). \tag{13}$$

- z=0
  If there is no external field, one obviously has $z = 0$. Then the above equation should be modified by

$$\begin{aligned} \mathcal{R}(t) &= \frac{1}{2}\frac{x_\Lambda^2 + y_\Lambda^2}{2}(\Gamma t)^2, \qquad (14) \\ \mathcal{R} &= \frac{x_\Lambda^2 + y_\Lambda^2}{2}. \qquad (15) \end{aligned}$$

3. Potential experimental searches

Now we discuss the experimental feasibility to measure the oscillation mass. With huge data sample, one can measure both the $\mathcal{R}$ and $|\lambda_{p\pi^-}|$. The time information can be also accessed, or in other words, both $\mathcal{R}$ and $\mathcal{R}(t)$ can be measured. From these quantities, the oscillation parameters will be determined reliably. As a first step, we can get an estimated value for $\delta m_{\Lambda\bar{\Lambda}}$ in the absence of an external field from Eq. (15). Assuming $y_\Lambda = 0$ one will get

$$\delta m_{\Lambda\overline{\Lambda}} = \frac{1}{\sqrt{2}}\sqrt{\mathcal{R}}\Gamma. \tag{16}$$

About 10×10^9 J/ψ samples can be collected per year at BEPC-II in Beijing [10, 11]. Provided that no signal events of $J/\psi \to \Lambda_H \Lambda_L \to (p\pi^-)(p\pi^-)$ or $(\overline{p}\pi^+)(\overline{p}\pi^+)$ are observed, one should bound the upper limit $\mathcal{R} \leq 4 \times 10^{-7}$ and correspondingly $\delta m_{\Lambda\overline{\Lambda}} \leq 10^{-15}$ MeV at the confidence level of 90%, inferring from the knowledge of interval estimation for very rare signal (see also Refs. [12, 13, 14, 15, 16]). At a super tau-charm factory [17], the luminosity will be increased to near 10^4 times compared to BESIII, and then the constraint for the oscillation is more severe, $\delta m_{\Lambda\overline{\Lambda}} \leq 10^{-17}$ MeV.

Note that $\Upsilon(4S)$ also has the same quantum numbers as J/ψ, i.e., $I^G(J^{PC}) = 0^-(1^{--})$, which can also decays to the coherent $\Lambda\overline{\Lambda}$ states. But considering the branching ratios and the data sample from Belle and BaBar dectors, BESIII is again the most promising candidate to detect it. The true measurement is desired to get more valuable information. At last we note that in Refs. [18, 19, 20, 21, 22] for the neutron-antineutron interaction, they are the Standard-Model calculation, and these neutron-antineutron oscillation effects are surely omitted. We also notice that the channel $B \to \Lambda\overline{\Lambda}l\bar{\nu}_l$ is interesting to prove the $\Lambda\overline{\Lambda}$ interaction as well as the weak interaction in B meson decay, looking form our experience in $B \to \pi\pi l\bar{\nu}_l$ decay [23, 24].

4. Conclusion

In conclusion, we propose a new way to probe the baryon-number violating signal by using the collider experiment. The expression for the oscillation mass has been derived. BESIII is capable of such measurements. For a first step forward, we estimate the oscillation mass in the absence of the external magnetic field. With one year's luminosity at BES-III, we can set an upper limit of $\delta m_{\Lambda\overline{\Lambda}} < 10^{-15}$ MeV at 90% confidence level, corresponding to about 10^{-6} s of $\Lambda - \overline{\Lambda}$ oscillation time. It will be the first search of $\Lambda - \overline{\Lambda}$ oscillation experimentally.

Acknowledge

The author X.W.Kang would like to express his appreciation for useful discussions from Hai-Bo Li. Some texts are based on their common publication [5]. This proceeding is funded by the Importation and Development of High-Caliber Talents Project of Beijing Municipal Institutions (CIT&TCD20140311) and the Beijing Natural Science Fund (KZ201510016019).

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