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CP violation in $J/\psi \to \Lambda\,\bar{\Lambda}$

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We study CP violation in $J/\psi \to \Lambda\bar{\Lambda}$ decay. This decay provides a good place to look for CP violation. Some observables are very sensitive to the Λ electric dipole moment d_Λ and therefore can be used to improve the experimental upper bound on d_Λ. CP violations in the lepton pair decays of J/ψ and Υ are also discussed.

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Up to now CP violation has only been observed in the neutral kaon system [1]. In order to isolate the source (or sources) responsible for CP violation, it is important to find CP violation in other systems. The measurement of the electric dipole moment of elementary particles is very promising as a place to look for further evidence of CP violation. A stringent experimental upper bound has been obtained for the neutron [2] and the electron [3]. But the bounds on Λ, Σ, and other particles are fairly weak. In this paper we study CP violation in $J/\psi \to \Lambda\bar{\Lambda}$ decay. We show that this decay is also a good place to look for CP violation. Moreover, it can be used to improve the experimental upper bound on the electric dipole moment of Λ. We also discuss CP violation in the lepton pair decays of J/ψ and Υ.

The most general decay amplitude

$$A(J/\psi \to \Lambda(p_1)\bar{\Lambda}(p_2))$$

can be parametrized as

$$A(J/\psi \to \Lambda\bar{\Lambda}) = \varepsilon^\mu \bar{u}_\Lambda(p_1)[\gamma_\mu(a+b\gamma_5)+(p_{1\mu}-p_{2\mu})(c+id\gamma_5)]v_{\bar{\Lambda}}(p_2)\ , \tag{1}$$

where ε^μ is the polarization of the J/ψ particle and in its rest frame $\varepsilon_\mu = (0,\boldsymbol{\varepsilon})$. If CP is conserved, $d=0$. The constants a, b, c, and d are in general complex numbers when contributions of the absorptive part in the decay amplitude are included.

CP invariance can be tested in $J/\psi \to \Lambda\bar{\Lambda}$ only if the polarizations of Λ and $\bar{\Lambda}$ can be measured. Therefore, we will study J/ψ decay to polarized Λ ($\bar{\Lambda}$). The density matrix for this decay in the rest frame of J/ψ can be defined as

$$\begin{aligned} R_{ij} = [\,&\bar{u}_\Lambda(p_1,\mathbf{s}_1)[\gamma_i(a+b\gamma_5)+(p_{1i}-p_{2i})(c+id\gamma_5)]v_{\bar{\Lambda}}(p_2,\mathbf{s}_2)\\ &\times\bar{v}_{\bar{\Lambda}}(p_2,\mathbf{s}_2)[\gamma_j(a^*+b^*\gamma_5)+(p_{1j}-p_{2j})(c^*+id^*\gamma_5)]u_\Lambda(p_1,\mathbf{s}_1)]\ , \end{aligned} \tag{2}$$

where i and j label three-vector components.

The CP-violating part of this density matrix is given by

$$\begin{aligned} R_{ij} &= r_{ij} + r^*_{ji}\ ,\\ r_{ij} &= i2ad^*p_j\left\{\frac{M^2}{2}(\mathbf{s}_1-\mathbf{s}_2)_i - \frac{2M}{M+2m}(\mathbf{s}_1-\mathbf{s}_2)\cdot\mathbf{p}p_i\right.\\ &\qquad\left. +imM(\mathbf{s}_1\times\mathbf{s}_2)_i + i\frac{2M}{M+2m}[\mathbf{s}_1\cdot\mathbf{p}(\mathbf{p}\times\mathbf{s}_2)_i - \mathbf{s}_2\cdot\mathbf{p}(\mathbf{p}\times\mathbf{s}_1)_i]\right\}\\ &\quad +2ibd^*Mp_j\{s_{2i}\mathbf{s}_1\cdot\mathbf{p} - s_{1i}\mathbf{s}_2\cdot\mathbf{p} + i[\mathbf{p}\times(\mathbf{s}_1-\mathbf{s}_2)]_j\}\\ &\quad +4icd^*Mp_ip_j\{-(\mathbf{s}_1-\mathbf{s}_2)\cdot\mathbf{p} + i(\mathbf{s}_1\times\mathbf{s}_2)\cdot\mathbf{p}\}\ , \end{aligned} \tag{3}$$

where $\mathbf{p}$ is the three-momentum of Λ, $\mathbf{s}_1$ ($\mathbf{s}_2$) are the polarization vectors of Λ ($\bar{\Lambda}$) defined in their rest frames, and M and m are the masses of J/ψ and the Λ particles, respectively. If J/ψ is produced at the threshold at $\bar{p}\,p$ or $e^+\,e^-$ colliders, the density matrix ρ_{ij} for the production of J/ψ can be written as

$$\rho_{ij} = \frac{1}{3}\delta_{ij} + \frac{1}{2i}\epsilon_{ijk}\hat{k}_kC - \left(\hat{k}_i\hat{k}_j - \frac{1}{3}\delta_{ij}\right)D\ , \tag{4}$$

where $\hat{\mathbf{k}}$ is the direction of the p or e beam, and C and D are constants which depend on the details of the beams.

In the experimental situation, the polarizations of the Λ particles are measured by analyzing their decays. We will use the main decay channels $\Lambda(\mathbf{s}_1) \to p(\mathbf{q}_1)+\pi^-$ and $\bar{\Lambda}(\mathbf{s}_2) \to \bar{p}(\mathbf{q}_2)+\pi^+$ to analyze the polarizations of the Λ particles. The density matrix for these two decays in the rest frame of Λ ($\bar{\Lambda}$), can be written as

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$$\rho_\Lambda = 1 + \alpha_- \mathbf{s}_1 \cdot \hat{\mathbf{q}}_1 \quad \text{for } \Lambda \text{ decay} ,$$
$$\rho_{\bar{\Lambda}} = 1 - \alpha_+ \mathbf{s}_2 \cdot \hat{\mathbf{q}}_2 \quad \text{for } \bar{\Lambda} \text{ decay} , \qquad (5)$$

where $\alpha_- \approx \alpha_+ = 0.642 \pm 0.013$ [4] and $\hat{\mathbf{q}}_i = \mathbf{q}_i/|\mathbf{q}_i|$.

Any experimental observables O can be constructed from $\mathbf{k}$, $\mathbf{p}$, and $\mathbf{q}_i$. The expectation value of O is given by

$$\langle O \rangle = \frac{1}{N}\frac{\beta}{8\pi}\frac{1}{(4\pi)^3}\int d\Omega_p\, d\Omega_{q_1}\, d\Omega_{q_2} O \mathrm{Tr}\{\mathrm{R_{ij}}\rho_{\mathrm{ji}}\rho_\Lambda \rho_{\bar{\Lambda}}\} , \qquad (6)$$

$$\begin{aligned} N &= \frac{\beta}{12\pi}(2|a|^2(M^2+2m^2) + 2|b|^2(M^2-4m^2) \\ &\quad + |c|^2(M^2-4m^2)^2 + 4Re(ac^*)m(M^2-4m^2) \\ &= 2M\Gamma(J/\psi \to \Lambda\bar{\Lambda}) , \end{aligned} \qquad (7)$$

where $\beta = \sqrt{1-4m^2/M^2}$, $d\Omega_i$ are the solid angles, and the trace is over the spins of the Λ particles. We find two observables which are particularly interesting:

$$A = \theta(\hat{\mathbf{p}}\cdot(\hat{\mathbf{q}}_1 \times \hat{\mathbf{q}}_2)) - \theta(-\hat{\mathbf{p}}\cdot(\hat{\mathbf{q}}_1 \times \hat{\mathbf{q}}_2)) ,$$
$$B = \hat{\mathbf{p}}\cdot(\hat{\mathbf{q}}_1 \times \hat{\mathbf{q}}_2) , \qquad (8)$$

where $\theta(x)$ is 1 if $x > 0$ and is zero if $x < 0$. A and B are CP-odd and CPT-even observables. Nonzero expectation values for them signal CP violation. In terms of the parameters a , b , c , and d, we have

$$\langle A \rangle = -\frac{\alpha_-^2 \beta^2}{48N} M^2[2m\mathrm{Re}(da^*) + (M^2-4m^2)\mathrm{Re}(dc^*)],$$
$$\langle B \rangle = -\frac{48}{27\pi}\langle A \rangle . \qquad (9)$$

The quantity $\langle A \rangle$ is equal to

$$\langle A \rangle = \frac{N^+ - N^-}{N^+ + N^-} , \qquad (10)$$

where $N^\pm$ indicate events with $\mathrm{sgn}[\mathbf{p}\cdot(\mathbf{q}_1\times\mathbf{q}_2)] = \pm$, respectively. $\langle B \rangle$ measures the correlations between the momenta. It is interesting to note that $\langle A \rangle$ and $\langle B \rangle$ are insensitive to CP violation in the Λ decay amplitude and are independent of the parameters C and D, e.g., independent of how J/ψ is polarized. One can also construct CP odd and CPT odd observables from $\mathbf{p}$, $\mathbf{k}$, and $\mathbf{q}_i$. These observables receive contributions from terms proportional to $\mathrm{Im}(da^*)$, $\mathrm{Im}(db^*)$, and $\mathrm{Im}(dc^*)$ and CP violation in the Λ decay matrix element. It is difficult to analyze these observables. CP violation in Λ decays has been studied in experiments with Λ from J/ψ decays [5]. But in this analysis CP violation from the J/ψ decay amplitude was neglected. No study has been performed of the observables $\langle A \rangle$ and $\langle B \rangle$. We will study these two observables in the following.

The branching ratio for $J/\psi \to \Lambda\bar{\Lambda}$ has been measured to be 1.35×10^{-3} [4]. From this we can obtain information about the parameters in the amplitude. The b term is a P-violating amplitude and is expected to be significantly smaller than the P-conserving a and c amplitudes. We will therefore neglect contribution from b. The relative strength of the amplitude a and c can be determined by studying correlations between the polarization of J/ψ and the direction of Λ momentum. Because of the large experimental errors the constants a and c cannot be reliably determined at present. In our numerical estimates we will consider two cases where the decay ampiltude is dominated by (1) the a term, and (2) the c term, respectively

The CP violating d term can receive contributions from different sources, the electric dipole moment, the CP violating Z-Λ coupling, etc. In the following we estimate the contribution from the electric dipole moment d_Λ of Λ. Here d_Λ is defined by

$$L_{\mathrm{dipole}} = i\frac{d_\Lambda}{2}\bar{\Lambda}\sigma_{\mu\nu}\gamma_5\Lambda F^{\mu\nu} , \qquad (11)$$

where $F^{\mu\nu}$ is the field strength of the electromagnetic field. Exchanging a photon between Λ and a c quark, we have the CP violating c-Λ interaction

$$L_{c-\Lambda} = -\frac{2}{3M^2}ed_\Lambda(p_1^\mu - p_2^\mu)\bar{c}\gamma_\mu c\bar{\Lambda}i\gamma_5\Lambda . \qquad (12)$$

From this we obtain

$$d = -\frac{2}{3}\frac{g_V}{M^2}ed_\Lambda . \qquad (13)$$

Here we have used the parametrization $< 0|\bar{c}\gamma_\mu c|J/\psi > = \varepsilon_\mu g_V$. The value $|g_V|$ is determined to be 1.25 GeV^2 from $J/\psi \to \mu^+\mu^-$.

Inserting the above numbers into Eq. (9), we obtain

$$|\langle A \rangle| = \begin{cases} 5.6\times10^{-3} d_\Lambda/(10^{-16}\, e\,\mathrm{cm}) , & \text{if the } a \text{ term dominates} \\ 1.25\times10^{-2} d_\Lambda/(10^{-16}\, e\,\mathrm{cm}) , & \text{if the } c \text{ term dominates} . \end{cases} \qquad (14)$$

Here we have used the absolute values for $\langle A \rangle$ because we cannot determine the relative signs for a, c, and d from the experimental data.

The experimental upper bound on d_Λ is 1.5×10^{-16} e cm [6]. There are constraints on the strange quark electric dipole moment and color dipole moment from the neutron electric dipole moment d_n [7], which follow if one assumes that the contributions to d_n do not cancel against each other. It is possible that cancellations do occur for d_n but not d_Λ and the constraints from d_n do not necessarily lead to strong constraints on d_Λ. Alternative experimental approaches to d_Λ, such as that presented here, should therefore be pursued. If d_Λ indeed has a value close to its experimental upper bound, the asymmetry $|\langle A \rangle|$ can be as large as 10^{-2}. Of course $\langle A \rangle$ can also be used to improve bound on d_Λ. With 10^7 J/ψ, it is already possible to obtain some interesting results. This experiment can be performed with the Beijing e^+

e^- machine. If 10^9 J/ψ can be produced, one can improve the upper bound on d_Λ by an order of magnitude. This can be achieved in future J/ψ factories. $|\langle B\rangle|$ will also give the same information. The same analysis can be easily applied to J/ψ decays into Σ, Ξ, etc.

Our analysis can also be used for J/ψ and $\Upsilon \to l^+l^-$. Assuming that the d term in Eq. (1) is mainly due to the electric dipole moment d_l of the leptons, we have

$$\langle A'\rangle = \frac{N'^+ - N'^-}{N'^+ + N'^-} = \frac{d_l}{e}\frac{\pi}{4}m_l\frac{\sqrt{1-4m_l^2/M^2}}{1+2m_l/M}\ , \qquad (15)$$

where m_l is the lepton mass, and $N'^\pm$ is the events with $\mathrm{sgn}[\mathbf{p}\cdot(\mathbf{s}_1\times\mathbf{s}_2)] = \pm$, respectively. Here $\mathbf{s}_i$ are the polarizations of the leptons. For $J/\psi \to \mu^+\mu^-$, we have, $|\langle A'\rangle| = 4\times 10^{-7}(d_\mu/10^{-19}\ e\,\mathrm{cm})$ which is too small to be measured experimentally. For $\Upsilon \to \tau^+\tau^-$, $|\langle A'\rangle| = 7\times 10^{-3} d_\tau/(10^{-16}\ e\,\mathrm{cm})$. The experimental upper bound on d_τ is $1.6\times 10^{-16}\ e\,\mathrm{cm}$ [8], so the asymmetry $\langle A'\rangle$ can be as large as 10^{-2}. Values of d_τ as large as $10^{-16} e\,\mathrm{cm}$ can be obtained in model calculations. The leptoquark model is one of them [9]. In this model there is a scalar which can couple to leptons and quarks. The couplings of the leptoquark scalar to the third generation are weakly constrained. It is possible to generate a large d_τ by exchanging a leptoquark at the one-loop level.

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