第 30 卷 第 9 期 高 能 物 理 与 核 物 理 Vol. 30, No. 9
2006 年 9 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Sep., 2006

Efficiency Correction to HOWL Generator of $J/\psi \to$ Baryon Antibaryon Decays*

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Abstract A kind of Monte-Carlo generator based on the transition amplitude information is developed to study the detection efficiency correction to the pure phase space(HOWL) generator. Monte-Carlo(MC) simulations for the $J/\psi \to p\bar{p}$, $\Lambda\bar{\Lambda}$, pX decays are carried out, and the results show that angular distributions for the decayed particles can well be reproduced. Compared with the HOWL generator, we find that the generator based on amplitude information will make a large correction to the detection efficiency. Therefore we recommend that a generator with a full transition information be used to simulate the long sequential decays.

Key words charmonium decays, Monte-Carlo simulation, invariant amplitudes

1 Introduction

Monte-Carlo simulation technique (MCST) is widely employed in experimental data analyses in high energy physics. For example, for determining the detection efficiency or handling systematic errors, MCST is used to generate raw data combined with the detector information. For simplicity, the pure phase space (HOWL) generators are commonly used to generate events. However, in e^+e^- collider, the produced particles, say, J/ψ or $\psi(2S)$ are polarized along the beam, and they decay into final particles with a specific angular distribution. On the other hand, the detector acceptance dose not cover the full space. This implies that the angular distribution of the final particle states should be taken into consideration for obtaining an accurate detection efficiency. From the viewpoint of experiments, if the detection efficiency is determined by the HOWL generator, the corrections from the angular distributions of the final particles should be included in the systematic error analysis. In principle, to generate an event with angular distribution can be realized by user adding angular sampling code in the HOWL generator based on the transition amplitude information as we developed in Ref. [1]. In this work, we investigate the angular distribution correction to the J/ψ sequential decays via $B\bar{B}$(B : baryon) using amplitude information.

This generator is based on the acceptance-rejection method of Monte-Carlo sampling (for details, see Ref. [1]) as illustrated in Fig. 1. We use HOWL to generate the pure phase space of an event, then we calculate the amplitude square $AMP2$ of a decay and then generate a random number $XFLAG \in (0,1)$. Before an event is accepted, we add a rule $XFLAG < [AMP2/\mathrm{MAX}(AMP2)]$ to single out a favorable event. In principle, events with a specific angular distribution can be successfully generated if the amplitude information is correctly provided by user.

Received 5 February 2006, Revised 11 April 2006
* Supported by National Natural Science Foundation of China (10447130, 10375074, 10491303)
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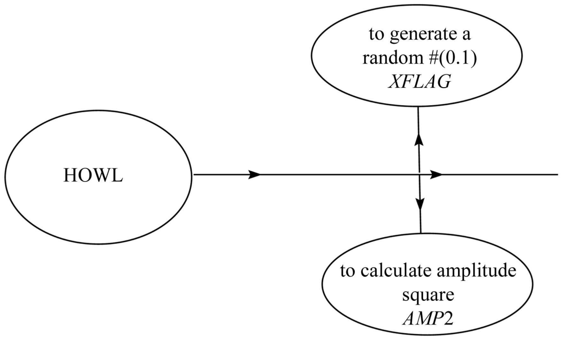

Fig. 1. An illustration of the scheme to generate events with specified angular distributions combined with transition amplitude information.

2 Construction of amplitude

For J/ψ → $p\bar{p}$, we use the helicity amplitude method, while for sequential decays, it is cumbersome to boost decayed particles into the center mass(CM) system of mother particles, so we present the tensor formalisms for J/ψ sequential decays.

2.1 J/ψ → $\mathbf{p\bar{p}}$ decay

For consideration of parity conservation in this decay, the helicity amplitudes satisfy:

$$F_{\frac{1}{2}\frac{1}{2}} = F_{-\frac{1}{2}-\frac{1}{2}}, \quad F_{-\frac{1}{2}\frac{1}{2}} = F_{\frac{1}{2}-\frac{1}{2}}. \tag{1}$$

The amplitude square reads:

$$|A|^2 = \frac{1}{2}\sum_{M,\lambda_1,\lambda_2} N_J^2 |F_{\lambda_1,\lambda_2} D^{1*}_{M,\lambda_1-\lambda_2}(\theta,\phi)|^2, \tag{2}$$

where N_J is a coupling constant. It is easy to get the angular distribution of proton (or antiproton) as follows:

$$\frac{\mathrm{d}N}{\mathrm{d}(\cos\theta)} \sim 1+\alpha\cos^2\theta \quad \text{with} \quad \alpha = \frac{|F_{\frac{1}{2},-\frac{1}{2}}|^2 - 2|F_{\frac{1}{2},\frac{1}{2}}|^2}{|F_{\frac{1}{2},-\frac{1}{2}}|^2 + 2|F_{\frac{1}{2},\frac{1}{2}}|^2}. \tag{3}$$

Where the angular distribution parameter α takes the value $\alpha = 0.676 \pm 0.036 \pm 0.042$[2].

2.2 J/ψ → $\mathbf{\Lambda\bar{\Lambda}, \Lambda \to p\pi}$ decay

For the sequential decay J/ψ → $\Lambda(p_5)\bar{\Lambda}(p_6)$, and then $\Lambda(p_5) \to \pi^-(p_1)\mathrm{p}(p_2), \bar{\Lambda}(p_6) \to \bar{\mathrm{p}}(p_3)\pi^+(p_4)$. The amplitude is constructed by the covariant tensor formalism. Since in the weak decay $\Lambda \to \mathrm{p}\pi$, the parity violation takes place. In this situation, the coupling of $\Lambda\mathrm{p}\pi$ is described by $\bar{u}(p',s')(A-B\gamma_5)u(p,s)$[3]. The amplitude of this decay can be expressed as:

$$\begin{aligned} M^{(\lambda)} = {} & \epsilon^{(\lambda)\mu}\bar{u}(p_2,s_2)(A-B\gamma_5)\frac{\not{p}_5+M_\Lambda}{p_5^2-M_\Lambda^2+\mathrm{i}\epsilon}\times \\ & (Z_\mu+g_2 Z_\nu \tilde{t}^{(2)\mu\nu})\frac{\not{p}_6-M_\Lambda}{p_6^2-M_\Lambda^2+\mathrm{i}\epsilon}\times \\ & (A-B\gamma_5)v(p_3,s_3), \end{aligned} \tag{4}$$

where $Z_\mu = \gamma_\mu - \frac{(p_1-p_2)_\mu}{m_\psi+2m_\mathrm{p}}$, and $\tilde{t}^{(2)\mu\nu}$ is the covariant tensor wave function for the orbital angular momentum $L=2$, and its full form can be found in Ref. [4]. $\lambda(=\pm1)$ is the J/ψ helicity. A and B are complex parameters which can be related to the Λ decay parameters α_- and ϕ by the relation[5]

$$\frac{A}{B} = \frac{|\boldsymbol{p}_\mathrm{p}|}{E_\mathrm{p}+m_\mathrm{p}}\,\frac{\cos\phi+\sqrt{\cos^2\phi-\alpha_-^2}}{\alpha_-}\,\mathrm{e}^{\mathrm{i}\phi}. \tag{5}$$

The coupling constant g_2 is determined by fitting the angular distribution of J/ψ → $\Lambda\bar{\Lambda}$ with $\alpha = 0.65$ by BESⅡ collaboration[6]. Since intermediate resonances Λ and $\bar{\Lambda}$ are long life particles, we use on-shell approximation for their propagator, i.e., $1/(p_i^2-M_\Lambda^2) \to -\mathrm{i}\pi\delta(p_i^2-M_\Lambda^2)$.

2.3 J/ψ → $\mathbf{pX, X \to K\bar{\Lambda}, \bar{\Lambda} \to \bar{p}\pi}$ decay

Recently, a threshold enhancement of $\mathrm{p}\bar{\Lambda}$ invariant mass has been observed in J/ψ decay[7]. We assume this sequential decay J/ψ → $\mathrm{p}(p_1)\mathrm{X}(p_5)$, $\mathrm{X}(p_5) \to \mathrm{K}(p_4)\bar{\Lambda}(p_6)$, $\bar{\Lambda}(p_6) \to \bar{\mathrm{p}}(p_3)\pi(p_2)$, and the X resonance is assumed with the quantum number $J^P = \frac{1}{2}^-$, then the amplitude can be expressed by:

$$\begin{aligned} M = {} & c_0\epsilon^\mu(p_0)\bar{u}(p_1,s_1)\Bigg[\gamma_\mu - \frac{(p_1-p_5)_\mu}{m_{\mathrm{J}/\psi}+M_\mathrm{X}+m_\mathrm{K}} + \\ & g_1\left(\gamma_\nu - \frac{(p_1-p_5)_\nu}{m_{\mathrm{J}/\psi}+M_\mathrm{X}+m_\mathrm{K}}\right)\tilde{t}^{(2)\mu\nu}\Bigg]\times \\ & \frac{\not{p}_5-M_\mathrm{X}}{p_5^2-M_\mathrm{X}^2+\mathrm{i}M_\mathrm{X}\Gamma}\gamma_5\tilde{g}_{\alpha\beta}\gamma^\alpha\tilde{t}^{(1)\beta}\times \\ & \frac{\not{p}_6-M_\Lambda}{p_6^2-m_\Lambda^2+\mathrm{i}\epsilon}(A-B\gamma_5)v(p_3,s_3), \end{aligned} \tag{6}$$

where $\tilde{t}^{(1)\beta}$ and $\tilde{t}^{(2)\mu\nu}$ are the covariant tensor wave functions for L=1 and 2, respectively. The coupling constant g_1 can be determined by the information of proton angular distribution. The X resonance parameters are assumed as $M_\mathrm{X} = 1.621\mathrm{GeV}$ and $\Gamma = 43\mathrm{MeV}$.

3 Generator and efficiency correction

For performance of MC simulation, we use the following generators:

1) HOWL: All particles are generated by the pure phase space;

2) Generator A: only the first chain of the decay $J/\psi \to B\bar{B}$ is generated by angular sampling, and the rest by HOWL generator;

3) Generator B: Events are generated based on transition amplitude information.

With the help of the tool GENBES on BEPC II [8], we carried out the MC simulation based on the above generators for $J/\psi \to p\bar{p}$, $\Lambda\bar{\Lambda}$, pX decays. We find that the angular distribution of the particles is well generated according to the input values.

Fig. 2 shows the angular distribution of the final particle states $p\bar{p}\pi^+\pi^-$ in sequential decay $J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi$ before tracking through the detector component. The $\Lambda(\bar{\Lambda})$ angular distribution parameter $\alpha_\Lambda = 0.66 \pm 0.02$ is well reproduced. It is interesting to note that in laboratory system, the direction of the outgoing proton($\bar{p}$) is almost along the $\Lambda(\bar{\Lambda})$ direction since they angular distribution parameters are almost the same. This result can be easily understandable since the mass of proton is heavier than pion's. Fig. 2(g),(h) shows that the angular distribution of proton and antiproton in Λ and $\bar{\Lambda}$ CM system. It is worthy to note that their angular distribution becomes so flat that it can be simulated by HOWL generator. This implies that the generated baryons Λ and $\bar{\Lambda}$ are averagely unpolarized. Since in the Λ rest frame, the angular distribution of proton takes the form[9]

$$\frac{\mathrm{d}N}{\mathrm{d}(\cos\theta_{\Lambda\mathrm{p}})} \sim 1 + \alpha_{\mathrm{p}} P_i \cdot \hat{q}, \tag{7}$$

where P_i is the Λ polarization, and $\hat{q}$ is the direction of the out-going proton.

The sequential decay of $J/\psi \to \Lambda\bar{\Lambda}$, $\Lambda \to p\pi$ can also be used to study the $\Lambda(\bar{\Lambda})$ decay constants by measuring the distribution of the $\cos(\widehat{p_{\mathrm{p}}p_{\bar{\mathrm{p}}}})$ in Λ and $\bar{\Lambda}$ CM system. N.A.Torquist formulates the differential cross-section as[10]:

$$\frac{\partial \Gamma}{\partial\cos\theta\,\partial\Omega'\,\partial\Omega''} \propto 2\left(1-\frac{p_\Lambda^2}{E_\Lambda^2}\sin^2\theta\right)(1-\alpha_\Lambda^2 a_n b_n)+ \frac{p_\Lambda^2}{E_\Lambda^2}\sin^2\theta[1-\alpha_\Lambda^2(\boldsymbol{a}\cdot\boldsymbol{b}-2a_x b_x)], \tag{8}$$

where $\boldsymbol{a}$ and $\boldsymbol{b}$ are the proton and antiproton momentum, respectively in the $\Lambda(\bar{\Lambda})$ rest frame, x is the direction orthogonal to the $\Lambda(\bar{\Lambda})$ direction and to the e^+e^- beam axis and $\boldsymbol{n}$ is an axis defined to take into account the suppression of spin-0 projection in the J/ψ decay. As measured by DM2 collaboration[11], the distribution of the $\cos(\widehat{p_{\mathrm{p}}p_{\bar{\mathrm{p}}}})$ can be fitted with a linear form. In Fig. 2(i), it is obvious to see that this distribution is well reproduced.

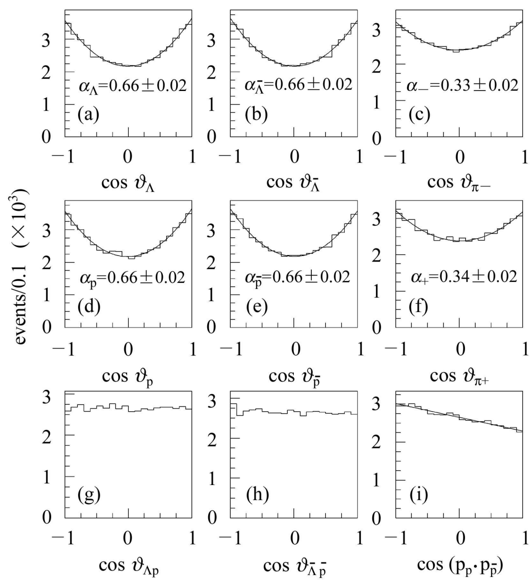

Fig. 2. Generator B: The angular distribution for the particles involved in $J/\psi \to \Lambda\bar{\Lambda}$ decay are given in laboratory system as shown from (a) to (f), where the polar angle of the outgoing particle is defined as the angle between the outgoing particle direction and the e^+e^- beam direction, while (g) and (h) correspond to the p and $\bar{p}$ angular distribution in Λ and $\bar{\Lambda}$ rest system, respectively, where the z-axis is along the outgoing direction of $\Lambda(\bar{\Lambda})$. (i) The distribution of $\cos(\boldsymbol{p}_{\mathrm{p}}\boldsymbol{p}_{\bar{\mathrm{p}}})$, where $\boldsymbol{p}_{\mathrm{p}}(\boldsymbol{p}_{\bar{\mathrm{p}}})$ is the proton(antiproton) momentum in $\Lambda(\bar{\Lambda})$ rest system.

Figure 3 shows the angular distributions for $p, \bar{p}$, K, π, Λ and X resonance in the sequential decay $J/\psi \to pX$, $X \to K^-\bar{\Lambda}, \bar{\Lambda} \to \bar{p}\pi$. In the simulation the angular distribution of proton can be set by adjusting the parameter g_1 in the amplitude. We find that the angular distribution parameter α is well reproduced compared with the input value. Fig. 3(b) shows that the angular distribution of the pion becomes very flat since its mass is much more less than proton's, and the direction of the outgoing Λ and proton almost fly along the mother particles particles. Similarly, we also find that in the Λ CM system, the $\bar{\mathrm{p}}$ angular distribution is of isotropic shape.

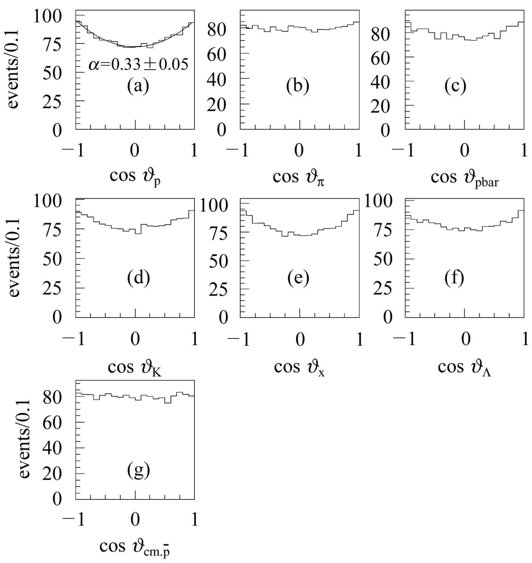

Fig. 3. Generator B: The angular distribution for the particles involved in $\mathrm{J}/\psi \rightarrow \mathrm{pX}$, $\mathrm{X} \rightarrow \mathrm{K}\bar{\Lambda}$, $\bar{\Lambda} \rightarrow \bar{\mathrm{p}}\pi$ decay is given in laboratory system as shown from (a) to (f), where the polar angle is defined as the angle between the direction of the outgoing particle and the $\mathrm{e}^+\mathrm{e}^-$ beam, while (g) corresponds to the antiproton angular distribution in $\bar{\Lambda}$ rest system, where the z-axis is taken along the outgoing $\bar{\Lambda}$ direction .

The detection efficiency depends on the event selection criteria. As for the $\mathrm{J}/\psi \rightarrow \mathrm{p}\bar{\mathrm{p}}$ decay, the selection criteria are chosen as those in Ref. [2]. For the $\mathrm{J}/\psi \rightarrow \Lambda\bar{\Lambda}, \mathrm{pX}$ decays, the $\mathrm{p}\bar{\mathrm{p}}$ tracks are selected with combined TOF and $\mathrm{d}E/\mathrm{d}x$ information, and for each event, the 4-C fit is performed and it is required that the probability of $\chi^2_{4\mathrm{C\text{-}fit}}$ should be greater than 1%. For selecting Λ candidates, it is required that $|m_{\mathrm{p}\pi} - m_{\Lambda}| < 0.01\mathrm{GeV}$.

For sequential decays, we find that the detector efficiency corrections to the HOWL generator are quite larger as shown in Table 1. For example, the efficiencies by generator A and B are lower by a factor of $(6.0 \sim 8.5)\%$ than that by HOWL. Especially for the long chain decay $\mathrm{J}/\psi \rightarrow \mathrm{pX}$, the generator B with full angular distribution information will contribute a large correction to the HOWL generator. Therefore we should recommend the generator with a full transitional information for simulating a long sequential decay.

Table 1. The detection efficiency correction to the HOWL generator for $\mathrm{J}/\psi \rightarrow \mathrm{B}\bar{\mathrm{B}}$ decays based on the generator A, B using the transition amplitude information. In the table, the value $\Delta\epsilon_{\mathrm{A}}/\epsilon$ ($\Delta\epsilon_{\mathrm{B}}/\epsilon$) corresponds to the generator A (B).

decay mode	$\mathrm{J}/\psi \rightarrow \mathrm{p}\bar{\mathrm{p}}$	$\mathrm{J}/\psi \rightarrow \Lambda\bar{\Lambda}$	$\mathrm{J}/\psi \rightarrow \mathrm{Xp}$
HOWL(ϵ_0)	$(54.9\pm0.5)\%$	$(23.5\pm0.3)\%$	$(9.7\pm0.1)\%$
generator A(ϵ_{A})	$(51.5\pm0.5)\%$	$(21.5\pm0.3)\%$	$(9.5\pm0.1)\%$
generator B(ϵ_{B})	$(51.5\pm0.5)\%$	$(22.1\pm0.3)\%$	$(8.6\pm0.1)\%$
$\Delta\epsilon_{\mathrm{A}}/\epsilon_0$	$(-6.2\pm0.7)\%$	$(-8.5\pm0.4)\%$	$(-2.1\pm0.1)\%$
$\Delta\epsilon_{\mathrm{B}}/\epsilon_0$	$(-6.2\pm0.7)\%$	$(-6.0\pm0.4)\%$	$(-11.3\pm0.1)\%$

4 Summary and conclusion

A kind of generator based on the transition amplitude information is developed to study the detection efficiency correction to the HOWL generator. The MC simulation for the $\mathrm{J}/\psi \rightarrow \mathrm{p}\bar{\mathrm{p}}, \Lambda\bar{\Lambda}, \mathrm{pX}$ decays is carried out, and the results show that the angular distributions for the decayed particles can well be reproduced. Compared with the HOWL generator, we find that the generator based on amplitude information will make a large correction to the detection efficiency. Therefore we should recommend using a generator with a full transition information to simulate the long sequential decays.

The authors thank Yuan Chang-Zheng for useful discussions and comments.

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J/ψ →重子+反重子衰变的HOWL产生子的效率修正*

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摘要　发展了一种基于跃迁振幅信息的Monte-Carlo产生子来研究纯相空间产生子(HOWL)的效率修正. 对J/ψ → $p\bar{p}$, $\Lambda\bar{\Lambda}$, pX衰变作了Monte-Carlo模拟, 结果表明, 这种产生子能够很好地实现末态粒子的角分布. 与HOWL产生子比较, 发现末态粒子的角分布会对效率产生很大的修正. 所以, 对于长链的级联衰变, 推荐这种基于跃迁振幅信息的产生子.

关键词　粲夸克偶数衰变　Monte-Carlo模拟　跃迁振幅

2006 – 02 – 05 收稿,　2006 – 04 – 11 收修改稿

∗ 国家自然科学基金(10447130, 10375074, 10491303)资助

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