MASTER

Baryon-Antibaryon Pair Decay of η_c in Coherent Production*

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ABSTRACT

We investigate the feasibility of observing η_c by its OZI-rule-forbidden baryon-antibaryon pair decay in the coherent production (Primakoff effect) of η_c . The cross sections are estimated as a function of photon energy, and the CM angular distribution is calculated.

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The existence of the 0^{-+} bound charmed quark and antiquark state in the vicinity of mass 2.8 GeV, usually called η_c ,¹ is expected to be experimentally confirmed in the radiative transitions from higher mass states of charmonium.^{2,3} This state may already have been seen at DORIS.⁴ Several authors have pointed out that it should also be possible to coherently photoproduce η_c in a Coulomb field (Primakoff effect)⁵; it would then be evidenced as a bump in the invariant mass spectrum of the two photons from the η_c decay.

Another method that has been suggested⁵ for detecting η_c produced via the Primakoff effect is to look for the production of baryon-antibaryon pairs from the decay of η_c . The purpose of this paper is to present a quantitative prediction for the pair production cross section and its angular distribution in the CM frame. Since η_c consists of a charmed quark-antiquark pair, its decay into ordinary baryon-antibaryon pairs proceeds via the violation of the Okubo-Zweig-Iizuka (OZI) rule.⁶ We first calculate the OZI-rule-violating Yukawa coupling of η_c with the baryon octet; this is then used to calculate the photo-production cross section for baryon-antibaryon pairs via an on-shell η_c . A bump in the invariant mass of any pair would then signal the existence of η_c and determine its mass.

The diagram illustrating the Primakoff production of η_c and its decay into baryon-antibaryon pairs is shown in Fig.1. The corresponding cross section^{2,5} is given by $(\sigma_{B\bar{B}} \equiv \sigma(\gamma Z \rightarrow Z\eta_c \rightarrow ZB\bar{B}))$

$$\sigma_{B\bar{B}}(E_\gamma) = \frac{4\pi Z^2 \alpha}{3 m_{\eta_c}} \frac{\Gamma(\eta_c \rightarrow \gamma\gamma)}{\Gamma(\eta_c \rightarrow \text{all})} \Gamma(\eta_c \rightarrow B\bar{B}) \mathcal{J}(E_\gamma), \quad (1)$$

where Z is the nucleus charge, $\Gamma(\eta_c \rightarrow \text{all})$ the total η_c width, and B indicates a baryon. $\mathcal{J}(E_\gamma)$ arises from the electromagnetic form factor of the target nucleus, and is given by⁷

$$J(E_Y) = \left\{ \frac{1}{4} \left[s - (M - m_{\eta_c})^2 \right] \left[s - (M + m_{\eta_c})^2 \right] \right\}^{\frac{3}{2}} \frac{s - M^2}{s^2} \\ \times \int_{-1}^1 d \cos \alpha \sin^2 \alpha |F(t)|^2 / t^2,$$

where α is the angle between the incident photon momentum and η_c momentum (see Ref.7, $F(t) = \exp(\langle r^2 \rangle t/6)$ the electromagnetic form factor with average charge radius squared $\langle r^2 \rangle = \frac{3}{5} (1.2 \text{ fm } A^{\frac{1}{3}})^2 = 780 \text{ GeV}^{-2}$ for a lead nucleus,⁵ t the momentum transfer between the initial and final nucleus states, M the target nucleus mass (194.8 GeV for lead), and $s = M^2 + 2ME_Y$ where E_Y is the laboratory photon energy. An identical expression holds for $\sigma_{\gamma\gamma}(E_Y)$ with the replacement of $\Gamma(\eta_c \rightarrow B\bar{B})$ by $\Gamma(\eta_c \rightarrow \gamma\gamma)$ in (1).

The widths $\Gamma(\eta_c \rightarrow \gamma\gamma)$, $\Gamma(\eta_c \rightarrow B\bar{B})$, and $\Gamma(\eta_c \rightarrow \text{all})$ are not known a priori. In the following numerical results, we shall use the ratio^{8,9}

$$\frac{\Gamma(\eta_c \rightarrow \gamma\gamma)}{\Gamma(\eta_c \rightarrow \text{all})} = \frac{8}{9} \frac{\alpha^2}{\alpha_s^2}, \quad (2)$$

with $\alpha_s = 0.19$, which follows from the simple quark model calculation of the amplitude ratio for $c\bar{c} \rightarrow \gamma + \gamma$ to $c\bar{c} \rightarrow \text{gluon} + \text{gluon}$. In this picture, $\Gamma(\eta_c \rightarrow \gamma\gamma)$ is predicted⁹ to be 8 keV. The determination of the width $\Gamma(\eta_c \rightarrow B\bar{B})$ is a more difficult problem because it involves OZI-rule violation, as mentioned earlier.

In the framework of the string picture, Freund and Nambu¹⁰ associated scalar, vector, and tensor closed strings (or "0" mesons) with the Pomeron or its daughter trajectories. Subsequently, Bolzan, Palmer, and Pinsky⁶ have associated the Pomeron with the cylinder swept out by the closed string, and then inferred the presence of the cylinder in the pseudoscalar channel.

In this manner, the OZI-rule-violating coupling of η_c to $B\bar{B}$ is found to be related to the usual pseudoscalar- $B\bar{B}$ coupling of η and η' to $B\bar{B}$. From Table I of Ref.6,

$$g_{\eta_c B\bar{B}} = 4.5 \times 10^{-3} g_{\eta B\bar{B}} + 3.32 \times 10^{-3} g_{\eta' B\bar{B}}. \quad (3)$$

In order to compute $g_{\eta_c B\bar{B}}$ from (3), we adopt the nonet scheme¹¹ for pseudoscalar mesons

$$P_9 = \begin{pmatrix} \frac{1}{\sqrt{2}} (\pi^0 + \eta) & \pi^+ & K^+ \\ \pi^- & \frac{1}{\sqrt{2}} (-\pi^0 + \eta) & K^0 \\ K^- & \bar{K}^0 & -\eta' \end{pmatrix}.$$

The interaction Hamiltonian is then given by

$$\mathcal{H}_{\text{INT}} = \sqrt{2}(f+d)\text{Tr}(B_8 \bar{B}_8 P_9) + \sqrt{2}(d-f)\text{Tr}(\bar{B}_8 B_8 P_9),$$

where B_8 is the usual matrix representation for the octet of baryons. The couplings obtained are presented in Table I. For the pion-nucleon-antinucleon coupling, $f+d = g$ and $g^2/4\pi = 14.6$. To obtain the remaining couplings of Table I, we must know the ratio $f/(f+d)$: there is general agreement¹² that this is in the range 0.245 to 0.40. We have used these extreme values to evaluate the $\eta_c B\bar{B}$ couplings in Table I. The baryon-antibaryon decay width of η_c is given by

$$\Gamma(\eta_c \rightarrow B\bar{B}) = \frac{1}{2} \frac{g_{\eta_c B\bar{B}}^2}{4\pi} \left(m_{\eta_c}^2 - 4m_B^2 \right)^{\frac{1}{2}}, \quad (4)$$

where m_B is the final state baryon mass. The results are presented in Table II.

The widths of Table II, and the ratio (2), determine the cross section (1). The cross sections for lead ($Z = 82$) are plotted in Fig.2. The energy dependence of all cross sections is the same. The difference arises from the $\eta_c B\bar{B}$ coupling (see Table II). They are of reasonable magnitude to envision experi-

mental measurement. Pairs should be relatively easy to find because of their long lifetimes, especially in neutral modes for which the charged background can be eliminated. Note that with the estimate⁹ $\Gamma(\eta_c \rightarrow \gamma\gamma) = 8 \text{ keV}$, the two photon decay cross section is typically only about 4% of the baryon-antibaryon cross section.

In Fig.3 we present the baryon (antibaryon) CM angular distribution for the energies $E_\gamma = 50, 100, 200, \text{ and } 300 \text{ GeV}$ on a lead target. It is given by

$$\begin{aligned} \left. \frac{d\sigma_{B\bar{B}}}{d\Omega} \right|_{\text{CM}} &= \frac{Z^2 \alpha}{\pi m_{\eta_c}^2 [m_{\eta_c}^2 - 4m_B^2]^{\frac{1}{2}}} \frac{\Gamma(\eta_c \rightarrow \gamma\gamma)}{\Gamma(\eta_c \rightarrow \text{all})} \Gamma(\eta_c \rightarrow B\bar{B}) \\ &\times \frac{s-M^2}{\sqrt{s}} \frac{[s-(M+m_{\eta_c})^2][s-(M-m_{\eta_c})^2]}{4s} \int dk_B^0 d\varphi' \frac{|F(t)|^2}{t^2} (1 - \cos^2 \alpha), \end{aligned} \quad (5)$$

where

$$\cos \alpha = \cos \theta \cos \omega + \sin \theta \sin \omega \cos \varphi',$$

$$\cos \omega = \frac{(s-M^2+m_{\eta_c}^2)k_B^0 - m_{\eta_c}^2 s^{\frac{1}{2}}}{|\vec{k}_B| [s-(M+m_{\eta_c})^2]^{\frac{1}{2}} [s-(M-m_{\eta_c})^2]^{\frac{1}{2}}},$$

$$t = -\delta + \beta \cos \alpha,^7$$

and θ and ω are the angles between the baryon momentum $\vec{k}_B$ and the photon and the η_c momenta, respectively, and φ' the azimuthal angle between the corresponding planes. The cross sections obtained by integrating the areas under the curves in Fig.3 agree with the values obtained from Fig.2.

The values for $d\sigma/dk_B^0$ are essentially constant over the range Δk_B^0 of the final baryon energies with variations up to 10% for higher energies.

These values may be approximated by

$$\frac{d\sigma_{B\bar{B}}}{dk_B^0} \approx \frac{\sigma_{B\bar{B}}}{\Delta k_B^0},$$

where

$$\Delta k_B^0 = \frac{1}{2\sqrt{s}} \left[s - (M - m_{\eta_c})^2 \right]^{\frac{1}{2}} \left[s - (M + m_{\eta_c})^2 \right]^{\frac{1}{2}} \left[1 - \frac{4m_B^2}{m_{\eta_c}^2} \right]^{\frac{1}{2}}.$$

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7. We take $t = -\delta + \beta \cos \alpha$, where $\delta = \left[(s-M^2)^2 - m_{\eta_c}^2 (s+M^2) \right] / 2s$, and $\beta = (s-M^2) \left[(s+M^2 - m_{\eta_c}^2)^2 - 4M^2 \right]^{1/2} / 2s$. The integral can be written explicitly:

$$\mathcal{J}(E_V) = \left\{ 1 + \left[\frac{\langle r^2 \rangle}{3} M^2 m_{\eta_c}^4 - (s+M^2) m_{\eta_c}^2 \right] / (s-M^2)^2 \right\} \left\{ E_1 \left(\frac{\langle r^2 \rangle}{3} (\delta - \beta) \right) - E_1 \left(\frac{\langle r^2 \rangle}{3} (\delta + \beta) \right) \right\}$$

$$- 2S \exp(-\langle r^2 \rangle \delta / 3) [\beta \cosh(\langle r^2 \rangle \beta / 3) + (\delta + 3/\langle r^2 \rangle) \sinh(\langle r^2 \rangle \beta / 3)] / (s-M^2)^2.$$

The function $E_1(x)$ is tabulated in the standard reference texts.
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TABLES

TABLE IYukawa Couplings in the Nonet Scheme.

$$g_{\eta \bar{N} N} = 3f - d$$

$$g_{\eta \bar{\Lambda} \Lambda} = 2(f - \frac{2}{3}d)$$

$$g_{\eta \bar{\Sigma} \Sigma} = 2f$$

$$g_{\eta \bar{\Xi} \Xi} = f - d$$

$$g_{\eta' \bar{N} N} = 0$$

$$g_{\eta' \bar{\Lambda} \Lambda} = \sqrt{2}(f + \frac{1}{3}d)$$

$$g_{\eta' \bar{\Sigma} \Sigma} = \sqrt{2}(d - f)$$

$$g_{\eta' \bar{\Xi} \Xi} = -2/\sqrt{2} f$$

TABLE II η_c Decay Width into Baryon-Antibaryon Pairs.

$f/(f+d)$	0.245	0.4
$\Gamma(\eta_c \rightarrow N \bar{N})$	0.13 keV	111 keV
$\Gamma(\eta_c \rightarrow \Lambda \bar{\Lambda})$	268 keV	98 keV
$\Gamma(\eta_c \rightarrow \Sigma \bar{\Sigma})$	227 keV	221 keV
$\Gamma(\eta_c \rightarrow \Xi \bar{\Xi})$	146 keV	150 keV
TOTAL BARYON	1.24 MeV	1.28 MeV

FIGURE CAPTIONS

Fig.1: Diagram illustrating coherent photoproduction of η_c and its subsequent baryon-antibaryon decay.

Fig.2: Cross sections for baryon-antibaryon production from a lead nucleus ($Z = 82$) as a function of lab photon energy, E_γ . We illustrate for $f/(f+d) = 0.245$ (see Table II). Individual baryon-antibaryon production cross sections can be scaled by the ratio of the respective partial width.

Fig.3: CM angular distributions for final-state baryons. We illustrate for $f/(f+d) = 0.245$ (see Table II). (a) $E_\gamma = 50$ GeV (b) $E_\gamma = 100$ GeV (c) $E_\gamma = 200$ GeV (d) $E_\gamma = 300$ GeV.

Fig.1

Fig.2

Fig.3