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SPIN ANALYSIS OF THE χ_b STATES

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ABSTRACT

Angular correlations in the cascade reaction $e^+e^- \to \Upsilon' \to \gamma\chi_b \to \gamma\gamma\Upsilon \to \gamma\gamma(\mu^+\mu^-$ or $e^+e^-)$ have been used to investigate the spins of two of the χ_b states. A dependence of the radiative transition rates on the χ_b spins has been examined. The results support the χ_b spins predicted by the potential models of heavy quarkonia.

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1. INTRODUCTION

According to the quarkonium model, the χ_b states are the lowest radial excitations of the P-wave (1^3P_J) in a system of bound $b\bar{b}$ quarks; thus their spins (J) are expected to be 0, 1 and 2. In the framework of potential models[2] the higher the spin the higher the mass of the χ_b state. An experimental verification of this spin assignment yields another test of the potential model description of the $b\bar{b}$ system.

Three χ_b states have been detected[3,4] as monochromatic lines in the inclusive photon spectrum from hadronic events taken on the Υ' resonance ($e^+e^- \to \Upsilon' \to \gamma\chi_b$, $\chi_b \to$hadrons). The angular distributions of photons coming from these transitions depend on the χ_b spin; however the spin cannot be studied in the inclusive way by using the angular distributions, since the resonance signals are observed on a very large background. The two higher mass χ_b states have also been observed[5,6] in the radiative cascade transitions between the Υ' and Υ resonances ($e^+e^- \to \Upsilon' \to \gamma\chi_b$, $\chi_b \to \gamma\Upsilon$, $\Upsilon \to \mu^+\mu^-$ or $\Upsilon \to e^+e^-$). There is no background problem in this channel. Although the number of observed events is small, a study of the angular correlations in the cascade sample provides the only chance to measure χ_b spins directly. We present this analysis in the next section.

The potential models predict a specific dependence of the transition rates for the radiative decays $\Upsilon' \to \gamma\chi_b$ and $\chi_b \to \gamma\Upsilon$ on the χ_b spins. Measured branching fractions for these processes may be used to investigate χ_b spins in a model dependent way. We discuss this problem in section 3.

The data for this analysis were collected with the Crystal Ball detector at the e^+e^- storage ring DORIS-II at DESY between Fall 1982 and Spring 1984. We accumulated an integrated luminosity of 63.1 pb^{-1} on the Υ' resonance corresponding to 201000 Υ' resonance decays.

The main part of the Crystal Ball detector[7] consists of a highly segmented spherical shell of NaI crystals. The good energy resolution for electromagnetically showering particles $\sigma(E)/E=2.7\ \%/\sqrt[4]{E}$ (E in GeV) plays the crucial role in this analysis, since it allows the complete resolution of the narrow fine structure of the χ_b states. Its uniform acceptance over a large solid angle (93 % of 4π) and good angular resolution for photons ($1^\circ - 2^\circ$) make the Crystal Ball well suited to study angular correlations in the $\gamma\gamma l^+l^-$ channel.

2. ANGULAR CORRELATIONS IN THE EXCLUSIVE CASCADE EVENTS

Events with two photons and two back-to-back muons or electrons have been selected using criteria very similar to those described in Ref.6. The energy distribution of the photon corresponding to the radiative decay of the Υ' in the final cascade sample is plotted in Fig.1. Two peaks at 107 and 131 MeV, with widths consistent with our energy resolution, correspond to the two higher mass χ_b states seen in the inclusive analysis of $\Upsilon' \to \gamma\chi_b$[4] (we will call them χ_b^α and χ_b^β states). Transitions to the third χ_b state (χ_b^γ) expected with photon energy at about 164 MeV are not seen in this channel with the present experimental statistics.

Within the ranges indicated in Fig.1 we obtain 66 events for the χ_b^α state and 71 events for the χ_b^β state. The numbers of $\gamma\gamma\mu^+\mu^-$ and of $\gamma\gamma e^+e^-$ events are roughly equal. The background contributions are estimated from the fit displayed in Fig.1. We find 4.4 ± 1.3 events in each χ_b sample coming from background processes (mainly from double radiative Bhabha scattering). Because of a low energy tail in the NaI line shape we expect a feed-down from the χ_b^β resonance to the χ_b^α sample of 3.3 ± 0.4 events. The overall background contribution is 12 % in the χ_b^α sample and 6 % in the χ_b^β sample.

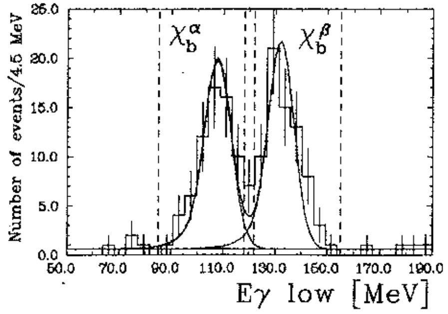

Figure 1. Energy distribution of the low energy photon in the sample of $\gamma\gamma\mu^+\mu^-$ and $\gamma\gamma e^+e^-$ events. The solid line shows the fit to the data of two monoenergetic γ-lines (asymmetric NaI line shape) and flat background. The dashed lines indicate the cuts defining the data samples for the spin analysis.

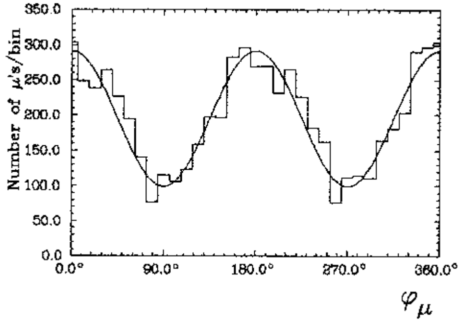

Figure 2. Azimuthal angular distribution of muons from $e^+e^- \to \mu^+\mu^-$ annihilation. The solid line displays the fit of the formula : $\Delta n/\Delta\phi \propto (1+\frac{1}{3}\cos^2\theta_o)+\mathrm{P}^2\cos 2\phi(1-\frac{1}{3}\cos^2\theta_o)$ where $\cos\theta_o$ is a cut on the polar angle with respect to the beam direction ($\cos\theta_o = 0.4$ has been used).
The beam polarization is P=75±5 %.

Given our small statistics data sample we must extract the maximum information about the χ_b spins analysing the full angular correlation in the cascade process. The full angular distribution can be described by 6 independent angles (directions of the two photons and direction of one of the final state leptons, which are exactly back-to-back in the Υ rest frame). It depends on the χ_b spin (J), the transition multipoles and the beam polarization (P).

In accordance with the quarkonium model we consider only three possible spin values of a χ_b state : 0, 1 or 2.

The radiative transitions via a spin 0 state must be pure electric dipole (E1). For χ_b states of spin 1 and 2 higher multipoles can contribute : magnetic quadrupole (M2) for spin 1 and up to electric octupole (E3) for spin 2. The single quark transition picture predicts negligible octupole transition rates[8] . In the nonrelativistic quark model we expect the quadrupole amplitudes to be very small, too. In fact the Crystal Ball results for charmonium[7] proved that all transitions in the cascade process were pure dipole, except for a possibly non-zero quadrupole amplitude in the radiative decay of the spin 2 χ_c state ($\Gamma_{M2}/\Gamma_{E1} = 12^{+52}_{-8}$ %). The magnetic quadrupole transitions, as relativistic effects, should be even more suppressed in the Υ family. The scaling rule[9] $\Gamma_{M2}/\Gamma_{E1} \propto (1/m_Q)^2$ (m_Q-quark mass) gives a suppression by a factor of about 9. In the analysis presented here we assume that all photon transitions

are pure dipole.

DORIS-II beams are highly transversely polarized at the Υ' energy. We obtain a value P= 75 ± 5 % measuring the QED process $e^+e^- \to \mu^+\mu^-$ as shown in Fig.2. In principle the transverse beam polarization provides no additional information beyond that obtainable from unpolarized beams, however it makes the differences in the angular distributions for various spins more pronounced. Monte Carlo studies show that with unpolarized beams we would need twice the statistics to have the same sensitivity for the χ_b spin determination.

After the transition multipoles and the beam polarization value have been fixed, the angular distribution in the cascade channel depends only on the χ_b spin. The theoretical formulae for these distributions may be found in Ref.9.

In the first step of our spin analysis we use the logarithmic likelihood for spin 0 :

$$\frac{1}{N}\sum_{i=1}^{N} ln\ W_{J=0}(\Omega_i) \tag{1}$$

as a test function for testing different spin hypotheses. Here Ω_i denotes the measured values of all 6 independent angles in the i^{th} event, N the number of events in the data sample and $W_J(\Omega)$ the theoretical formula for the angular correlation function for spin J.

Each χ_b sample yields a value of the test function. We compare these values with the probability density distributions of the test function (1) under all three spin hypotheses J=0,1,2. To obtain these distributions we generate Monte Carlo (M.C.) events according to each spin hypothesis. We simulate the detector response for these events and then we apply the same selection procedure to the M.C. data as used for real events. M.C. events which survive all cuts are grouped into experiments with the same statistics as found in the true data sample. A large number of the M.C. experiments has been generated for each spin hypothesis. The distributions of the test function are gaussian, as expected from the Central Limit Theorem (see curves in Fig.3). Their mean values are independent of the number of events N in the experiment and their widths vary like $1/\sqrt{N}$. The predicted distributions for the χ_b^α (Fig.3) and χ_b^β (Fig.4) samples are almost identical since the numbers of observed events in both data samples are very similar. The difference between the experimental value of the test function and the mean value of the distribution of this test function under the spin 0 hypothesis is 2.9 standard deviations for the χ_b^α sample and 5.2 standard deviations for the χ_b^β sample. The corresponding confidence levels for this hypothesis being true are $0.19^{+0.28}_{-0.12}$ % and $0.00001^{+0.00007}_{-0.00001}$ % respectively (one side probabilities), thus ruling out spin 0 for the χ_b^α and χ_b^β states. The errors quoted for the confidence levels come from systematic effects : uncertainty in the beam polarization value, possible consequences of the background in the data samples, the limited number of M.C. experiments used in the calculations. The data favour the expected spin 2 for the χ_b^α and spin 1 for the χ_b^β, however the effect is not significant enough to draw a firm conclusion about the spin 1 and spin 2 assignments.

One may apply other test functions to distinguish between the spin 1 and spin 2 hypotheses.

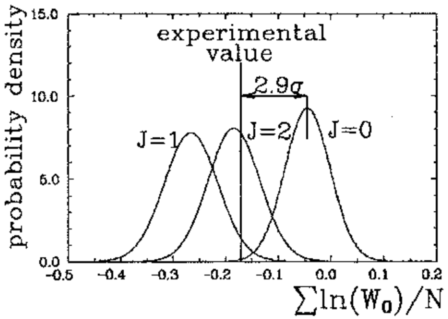

Figure 3. Tests with use of the likelihood for spin 0 for the χ_b^α sample (expected spin J=2). The confidence level for the spin 0 hypothesis is $0.19^{+0.28}_{-0.12}$ %. The gaussian curves represent the M.C. predictions of the test function distributions under the spin hypotheses J. The vertical line represents the value of the test function obtained from the real data.

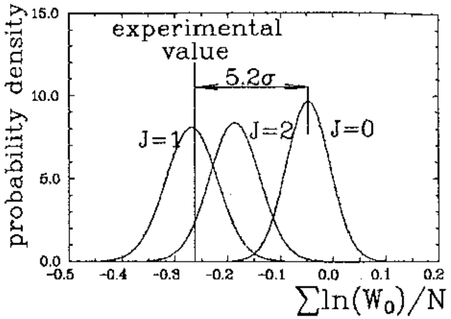

Figure 4. Tests with use of the likelihood for spin 0 for the χ_b^β sample (expected spin J=1). The confidence level for the spin 0 hypothesis is $0.00001^{+0.00007}_{-0.00001}$ %.

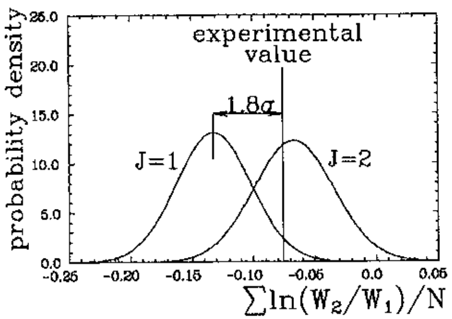

Figure 5. Likelihood ratio tests for the χ_b^α sample (expected spin J=2). The confidence level for the spin 1 hypothesis is $3.6^{+4.5}_{-0.7}$ %.

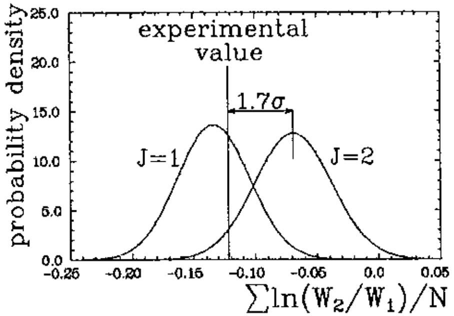

Figure 6. Likelihood ratio tests for the χ_b^β sample (expected spin J=1). The confidence level for the spin 2 hypothesis is $4.5^{+1.0}_{-1.6}$ %.

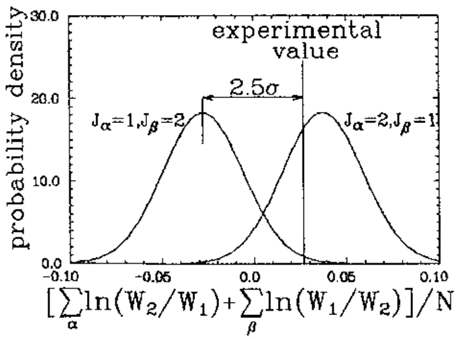

Figure 7. Likelihood ratio tests for the combined data of the χ_b^α and χ_b^β samples (expected spin assignment $J_\alpha = 2$, $J_\beta = 1$).
The confidence level for the spin hypothesis $J_\alpha = 1$, $J_\beta = 2$ is $0.6^{+0.8}_{-0.2}$ %.

The likelihood ratio test based on the test function :

$$\frac{1}{N}\sum_{i=1}^{N} \ln[W_{J=2}(\Omega_i)/W_{J=1}(\Omega_i)] \tag{2}$$

is supposed to be the most powerful one[10]. As presented in Fig.5-6 , the data favour again the expected spins, however they do not allow to strictly rule out the reverse spin assignments. The confidence level for the J_α=1 hypothesis is $3.6^{+4.5}_{-0.7}$ % and for the J_β=2 hypothesis is $4.5^{+1.0}_{-1.6}$ %.

We can double the experimental statistics combining data from both χ_b samples to test the global spin assignment : $J_\alpha = 1$, $J_\beta = 2$ against $J_\alpha = 2$, $J_\beta = 1$. We use again the likelihood ratio test (Fig.7) with the test function :

$$\frac{1}{N_\alpha + N_\beta}\left(\sum_{i=1}^{N_\alpha} \ln[W_{J=2}(\Omega_i)/W_{J=1}(\Omega_i)] + \sum_{j=1}^{N_\beta} \ln[W_{J=1}(\Omega_j)/W_{J=2}(\Omega_j)]\right) \tag{3}$$

The data agree very well with the expected spin assignment $J_\alpha = 2, J_\beta = 1$. The hypothesis $J_\alpha = 1, J_\beta = 2$ (confidence level $0.6^{+0.8}_{-0.2}$ %) is ruled out. This result is obtained under the assumption of pure electric dipole radiative transitions. The results for ruling out spin 0 do not involve any assumptions.

3. RADIATIVE TRANSITION RATES

The potential model prediction $\Gamma_{E1}(^3S_1 \to {}^3P_J) \propto (2J+1)\cdot E_\gamma^3$ can be used to obtain an additional support for the χ_b spins expected in the standard quarkonium model. We calculate $\Gamma^\circ = \Gamma(\Upsilon' \to \gamma\chi_b)/(2J+1)\cdot E_\gamma^3$ from the measured intensities of the corresponding peaks in the inclusive photon spectrum on the Υ' resonance[4]. We take into account the dependence of the detection efficiency on J. The reduced transition widths should be in the relative ratio $\Gamma_\alpha^\circ : \Gamma_\beta^\circ : \Gamma_\gamma^\circ = 1:1:1$ for the correct spin assignment. In fact, the result for $J_\alpha = 2, J_\beta = 1, J_\gamma = 0$ fits very well to this prediction: $\Gamma_\alpha^\circ : \Gamma_\beta^\circ : \Gamma_\gamma^\circ = (0.89 \pm 0.14 \pm 0.16) : 1 : (0.84 \pm 0.21 \pm 0.21)$. All other spin assumptions lead to results, which are far away from the expectation. For example the inverse spin assignment $J_\alpha = 0, J_\beta = 1, J_\gamma = 2$ gives $\Gamma_\alpha^\circ : \Gamma_\beta^\circ : \Gamma_\gamma^\circ = (4.92 \pm 0.80 \pm 0.91) : 1 : (0.15 \pm 0.04 \pm 0.04)$.

A last hint about the χ_b spins comes from the the fact, that the χ_b^γ state is not observed in the cascade channel, which must be related to the small branching ratio of $\chi_b^\gamma \to \gamma\Upsilon$. Although the transition widths $\Gamma_{E1}(^3P_J \to {}^3S_1) \propto E_\gamma^3$ do not depend on the χ_b spin, a spin dependence of the branching ratios is introduced by different hadronic widths of the χ_b states, as predicted by QCD. Using the formula $\Gamma_{had}(\chi_b) \propto E_\gamma^3 \cdot (1/BR(\chi_b \to \gamma\Upsilon) - 1)$ applied to our results for $BR(\chi_b \to \gamma\Upsilon)$, obtained from a combination of the inclusive[4] and exclusive[6] results, we find the relatively large hadronic width of the χ_b^γ state : $\Gamma_{had}^\gamma > 5.0 \cdot \Gamma_{had}^\alpha$ at 90 % C.L. This is expected in the QCD calculations[11] for the spin 0 state ($\Gamma_{had}^{J=0} = 5.5 \cdot \Gamma_{had}^{J=2}$).

4. CONCLUSIONS

The analysis of angular correlations in the cascade process $e^+e^- \to \Upsilon' \to \gamma\chi_b \to \gamma\gamma\Upsilon \to \gamma\gamma(e^+e^-\ or\ \mu^+\mu^-)$ allows us to rule out with the high confidence spin 0 for the both χ_b states observed in this channel. Assuming pure electric dipole photon transitions we can also exclude at 99.4 % C.L. the global spin assignment : J=1 for the highest mass χ_b state and J=2 for the second highest mass χ_b state. The data agree very well with the χ_b spins predicted by the potential models of heavy quarkonia.

The radiative transition rates for the $\Upsilon' \to \gamma\chi_b$ and $\chi_b \to \gamma\Upsilon$ exhibit the expected spin dependence under the standard spin assignment to the χ_b states.

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