ANGULAR DISTRIBUTIONS IN THE REACTIONS $p\bar{p}\to\chi_{1,2}\to\gamma\psi\to\gamma e^+e^-$

R704 Collaboration
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Received 11 June 1987

In the experiment R704 at the CERN Intersecting Storage Rings, the two p-wave charmonium states χ_1 and χ_2 were formed directly in proton–antiproton annihilation, and detected through the decay chain $\chi_J\to\gamma+J/\psi\to\gamma+e^+e^-$. The angular distributions of the events found are studied here. A maximum likelihood analysis shows that the χ_1 radiative transition to the J/ψ is compatible with a pure dipole. Indications of a nonzero, positive quadrupole contribution to the χ_2 radiative transition are found. Finally, it is found that the χ_2 data are consistent with the conventional assumption that a single quark radiates the photon in the transition from the χ_2 to the J/ψ.

1. Introduction. In the experiment R704 at the CERN Intersecting Storage Rings (ISR), the χ_1 and χ_2 charmonium states were formed directly in proton–antiproton annihilation and detected by tagging the final state $\gamma+e^+e^-$ arising from the decay chains $\chi_J\to\gamma+J/\psi\to\gamma+e^+e^-$. The angular distributions of these reactions,

$$p\bar{p}\to\chi_J\to\gamma+J/\psi\to\gamma+e^+e^-,\quad J=1,2\,, \tag{1}$$

depend on several parameters which are of interest for the study of the charmonium system and of perturbative quantum chromodynamics (QCD). The multipole nature of the $p\to s$ wave transitions may be investigated by studying the angular distributions. The relative importance of the multipole components may in turn be related to the quark magnetic moment [1]. Assuming the validity of the QCD helicity selection rule, specific predictions for the angular distributions can be made in the dipole approximation [2,3]. In ref. [3], it is shown that for the χ_2 case, the shape of the distribution is very sensitive to the values of the two parameters B_0, the amount of net helicity zero in the formation process, and a_2, the magnetic quadrupole component of the

[1] Deceased July 21, 1984.

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(North-Holland Physics Publishing Division)

$\chi_2 \rightarrow \gamma + J/\psi$ transition. Furthermore, in ref. [4] it is pointed out that the hypothesis that a single quark radiates the photon in the radiative transitions may be tested by studying the angular distribution (1) for the χ_2 case.

2. Experimental layout. In this experiment, the charmonium states were formed by letting antiprotons circulate in one of the rings of the CERN ISR, where a target system consisting of a hydrogen gas "jet" crossing the beam tube was mounted. This resulted in proton–antiproton interactions at very high luminosities, and a small interaction volume of less than 1 cm^3. The R704 detector system consisted of two spectrometer arms mounted symmetrically around the interaction region, covering the polar angle of 17° to 66° (in the laboratory frame, with the origin in the centre of the interaction region). Each arm covered 45° in azimuth and consisted of a section designed for charged-particle tracking, followed by a segmented electromagnetic calorimeter. The first part consisted of a set of scintillation hodoscopes for triggering, a set of multiwire proportional chambers (MWPCs) for tracking, and a threshold Cherenkov counter for electron identification. The calorimeter part consisted of a lead/scintillator sandwich ($5X_0$), proportional chambers with analog readout of the strips, separated by 1 cm (10 mrad), and a lead–glass wall ($10X_0$). This design of the calorimeter would meet the requirements of separating one from two showers, and the ability of discriminating between electromagnetic and hadronic showers. The part of the forward hemisphere not covered by the detector arms was covered by a coarsely segmented veto system capable of distinguishing photons from charged particles. A detailed description of the experimental technique and apparatus is found in ref. [5].

3. Event selection. This study is based on the event sample resulting from the analysis described in ref. [6]. The event selection is based on identifying a pair of electrons, one in each arm, yielding an invariant mass (from direction and energy measurements in the detectors) which is consistent with the J/ψ mass. In addition, the response of the rest of the detector and the veto counters was required to be consistent with a γ both from topological considerations and from the kinematics of reaction (1). Whenever, for kinematical reasons, a photon was expected to miss the detector and veto system entirely, the event was accepted if the detector response was consistent with this expectation. In addition to the 30 χ_1 and 50 χ_2 quoted in ref. [6], 4 χ_2 events found in an early test run were included in the sample used in this study. A conservative limit to the background contamination in the sample may be estimated from the off-resonance data taken during a search for the $^1P_1$ charmonium state [7]. No events fitting reaction (1) were found in the 309 nb^{-1} of integrated luminosity collected. Assuming a flat background, this puts an upper limit to the background in the χ samples of 8.2 events (84% CL), where 1369 nb^{-1} were collected.

4. Analysis of the angular distributions. Three angles are necessary to describe the full angular distributions:

θ: the polar angle of the photon with respect to the antiproton beam, defined in the centre-of-mass system;

θ': the angle of the positron with respect to the J/ψ direction of flight, defined in a frame where the J/ψ is at rest;

ϕ': the azimuthal angle of the positron in the J/ψ frame (the primed frame), where the x' axis is lying in the plane spanned by the photon and the antiproton.

Within the helicity formalism, the angular distributions of reactions (1) are discribed by $B_{|\lambda_1-\lambda_2|}$, where λ_1 and λ_2 are the proton and antiproton helicities; and $A_{|\lambda_3-\lambda_4|}$, where λ_3 and λ_4 are the γ and the ψ helicities, respectively; $\lambda_1-\lambda_2$ is constrained to be equal to M, the component of the χ_J spin onto the $p\bar{p}$ axis, and $\lambda_3-\lambda_4$ should be equal to the component of the χ_J spin onto the J/ψ–γ axis.

There are at most five parameters to be determined, constrained by two normalization conditions given by (following the conventions of ref. [3])

$$B_0^2+2B_1^2=1, \quad A_0^2+A_1^2+A_2^2=1 .$$

Thus, we are left with at most three free parameters, depending on the spin of the χ_J state under study. The parameters $A_0, ..., A_J$ may in turn be expressed in terms of the multipole coefficients, $a_1, ..., a_{J+1}$ [8,3].

For the different χ_J spins, we note the following:

$J=0$: Angular momentum conservation implies that $B_1=A_1=A_2=0$. The χ_0 angular distribution is therefore completely specified;

$J=1$: Angular momentum conservation implies $A_2=0$ (and equivalently $a_3=0$). Furthermore, we note that in order to conserve angular momentum, parity, and charge conjugation in the annihilation process, the χ_1 must be formed in p-wave ($L=1$), with the proton and antiproton spins coupled to $S=1$. Since the component of the orbital angular momentum along the $p\bar{p}$ axis must be zero, we find that the Clebsch–Gordan coefficient for coupling $S=1$ and $L=1$ to $J=1$ and $M=0$ is equal to zero. Hence, the χ_1 distribution is specified by just one unknown parameter, a_2;

$J=2$: All three parameters are allowed by angular-momentum conservation. However, assuming that a single quark radiates the photon in the transition $\chi_2 \to \gamma + J/\psi$, only the two lowest multipole transition amplitudes are allowed. Hence, the angular distribution should be specified by two unknown parameters, B_0 and a_2. By allowing for a nonzero value of the octupole component a_3, we may test the single-quark radiation (SQR) hypothesis.

The data are analysed by means of three-dimensional histograms over the three angles, using a maximum-likelihood method. The three subprocesses $p\bar{p} \to \chi_J$, $\chi_J \to \gamma + J/\psi$, and $J/\psi \to e^+e^-$ are separately invariant under parity transformations. Parity transformations were applied to the events in order to restrict the range of $\cos\theta$ and $\cos\theta'$ to positive values only [#1]. This provided an enhancement of the statistics in the remaining volume by a factor of four.

The data were divided into a total of 45 bins, three $\cos\theta$ and $\cos\theta'$ bins ranging from zero to one, and five bins in ϕ, ranging from 0 to 2π. The events were assumed to be distributed among the bins according to a multinominal distribution law:

$$L(N, \boldsymbol{n}, \boldsymbol{p}, B_0, a_2, \ldots) = N! \prod_{i=1}^{45} (p_i^{n_i}/n_i!) ,$$

$$\sum_{i=1}^{45} p_i \equiv 1 , \tag{2}$$

where N is the total number of events, n_i is the number of events in bin i, and p_i is the probability that an event will fall into bin i. This probability is a function of the undetermined parameters and is given by

$$p_i = \frac{\int_{\Delta\Omega} W(\theta, \theta', \phi', B_0, a_2, \ldots)\epsilon(\theta, \theta', \phi')\,d\Omega}{\int_{\text{full space}} W(\theta, \theta', \phi', B_0, a_2, \ldots)\epsilon(\theta, \theta', \phi')\,d\Omega} , \tag{3}$$

where $W(\theta, \theta', \phi', B_0, a_2, \ldots)$ is the theoretical distribution, a function of the angles and the unknown parameters, and $\epsilon(\theta, \theta', \phi')$ is the overall detection efficiency at the specified angles. In order to estimate ϵ, the space of angles was divided into $15\times15\times15=3375$ cells and ϵ was determined within each cell by a Monte Carlo simulation which took into account the geometrical acceptance and the uneven detection efficiency. Each of the 45 bins contains 75 cells, and the expression above is approximated by:

$$\sum_{j=1}^{75} W_{ij}\epsilon_{ij}\Delta\Omega_{ij} \Bigg/ \sum_{i=1}^{45} \left(\sum_{j=1}^{75} W_{ij}\epsilon_{ij}\Delta\Omega_{ij} \right), \tag{4}$$

where W_{ij} and ϵ_{ij} are averages of the theoretical distributions and detection efficiencies over the range of cell ij. The 75 numbers, ij, $j=1, 2, \ldots 75$, are the appropriate cells within bin i of the likelihood function, eq. (2).

The most probable values of the parameters B_0, a_2, ... are those which maximize the likelihood function. In order to find the parameters, the negative logarithm of the likelihood function was minimized using the MINUIT [10] program package.

In order to check the above method, events were generated according to angular distributions for several different values of the parameters to be determined. Subsequently, events were selected by imposing acceptance and efficiency criteria. Finally, the events were subjected to the maximum-likelihood analysis. This procedure proved very useful when debugging the program performing the likelihood analysis. The input parameters were reproduced to within the errors given by the analysis.

5. *Results.* Table 1 gives the results of the likelihood analyses of the two samples for various assumptions. The cited parameter values are those

[#1] Reducing the range of some variables by parity transformations has also been employed in similar analyses in ref. [9].

Table 1
Results of the likelihood fits.

Sample	Assumptions	$\|B_0\|$	a_2	a_3
χ_1	$J=1$ (and $B_0=0$)		-0.13 ± 0.19	
χ_2	$J=2$	<0.8	0.47 ± 0.26	0.09 ± 0.2
	$J=2, a_3=0$	<0.7	$0.46^{+0.19}_{-0.18}$	

giving a maximum to the likelihood function. The errors quoted are obtained by finding the values of the parameters at points where the value of the likelihood function is reduced to exp $(-\frac{1}{2})$ of its value at the maximum. In figs. 1a and 1b we display the raw distributions of the photons for the χ_1 and χ_2 samples together with the distributions to be expected at the best estimates of the parameters. Likelihood contours in the B_0–a_2 plane are shown in figs. 2a and 2b.

Finally, we performed a spin analysis using a likelihood-ratio test. The experimentally measured logarithm of the ratio of the likelihoods for two specific spin-helicity assumptions was compared to the distribution of this quantity found by performing a large number of Monte Carlo experiments with the same number of events (30 for the χ_1 and 54 for the χ_2 spin tests). Spin 1 events were generated with $a_2=0$ (pure dipole), and spin 2 events were generated with $B_0=0.45$ and $a_2=0.46$, which are the values that describe the χ_2 experimental data best . The results are illustrated in fig. 3. For the χ_1 data it was found that the confidence level of spin 0 was 7.5%, using the logarithm of the ratio between the likelihoods for spin 0 and spin 1 as a test function. The confidence of spin 1 from this test was 50.4%. Since we could not make any meaningful a priori assumptions on B_0 and a_2 for the spin 2 hypothesis, we could not construct a sensible spin 2 test of the χ_1 data.

Moreover, the χ_2 data were tested against the spin 0 and the spin 1 hypotheses. It was found that the spin 0 hypothesis was rejected with a confidence level of 0.5%, and the spin 1 hypothesis had a confidence level of 2.6% when the ratio tests were used (spin 0 against spin 2 and spin 1 against spin 2 respectively). Repeating the tests of the χ_2 data with the a_2 value for the spin 2 hypothesis moved by one standard deviation with respect to the fitted value of 0.46 did not change the confidence levels for spin 0 and

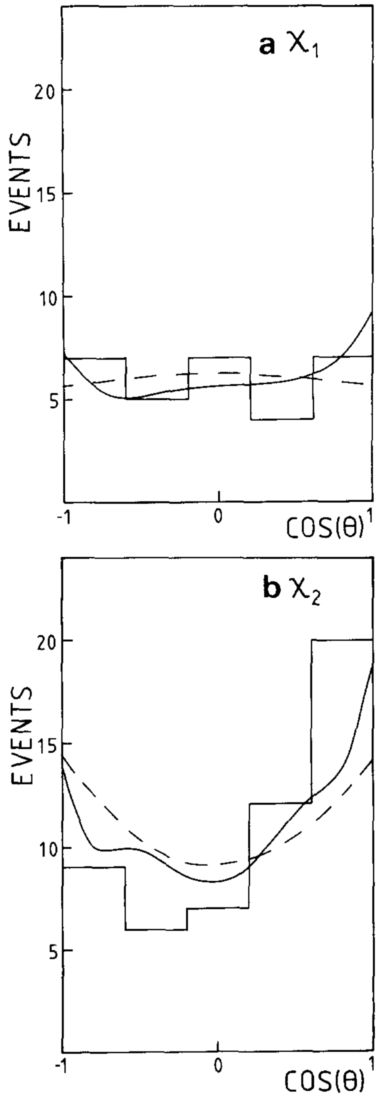

Fig. 1. Distribution of the angle of the photon with respect to the proton–antiproton axis θ for (a) the χ_1 and (b) the χ_2 events. The dashed line indicates the theoretical distribution for the preferred values of the parameters. The solid line indicates the distribution expected for these values of the parameters when the detector acceptance is taken into account.

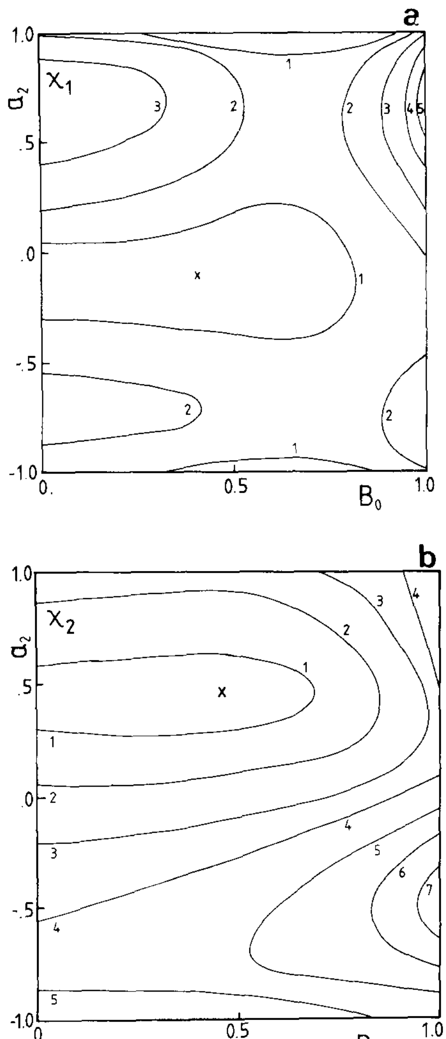

Fig. 2. Likelihood contours in the B_0–a_2 plane for (a) the χ_1 and (b) the χ_2 events. Contour number n corresponds to a decrease of the likelihood function by a factor exp $(-0.5n^2)$ with respect to its maximal value. The maximum of the likelihood function is indicated by a cross.

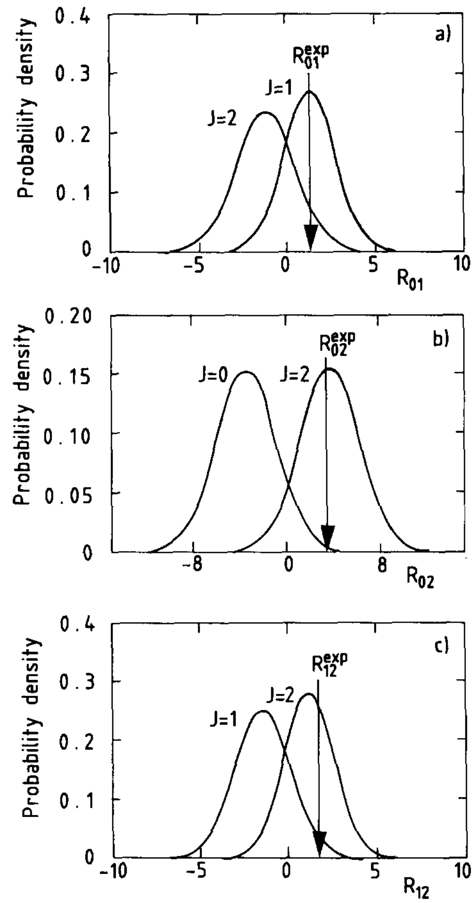

Fig. 3. (a) Spin 0 test for the χ_1 data. The quantity $R_{01} = -\ln(L_0/L_1)$ from the experimental data is compared to the distribution of this quantity expected for spin 0 events and that expected for spin 1 events. L_0 is the likelihood for spin 0, and L_1 is the likelihood for spin 1. The distributions were found by Monte Carlo simulation, and it was found that they could be very well approximated by gaussians. (b) Same as (a) for the χ_2 data, $R_{02} = -\ln(L_0/L_2)$ where L_0 is the likelihood for spin 0, and L_2 is the likelihood for spin 2 with the experimentally found values of the parameters from the χ_2 sample. (c) Same as (b), but here the χ_2 data are tested against a spin 1 hypothesis.

spin 1 significantly. More details of the analysis are found in ref. [11].

6. Conclusions. The angular distributions of the two processes $p\bar{p} \to \chi_J \to \gamma + J/\psi \to \gamma + e^+e^-$ ($J=1, 2$) have been studied. It is found that while the χ_1 radiative transition to the J/ψ is compatible with a pure dipole transition, a magnetic-quadrapole component seems to be present in the χ_2 transition. This has also been reported in another experiment [12], but the signs of the quadrupole amplitude disagree. Furthermore, the octupole component, a_3, of the χ_2 transition to the J/ψ is compatible with zero, in agreement with expectation assuming the validity of the SQR rule. However, the data are not very constraining, owing to the limited statistics.

This experiment would not have been possible without the active support of Professor H. Schopper. The following people are gratefully acknowledged for their technical contributions, of crucial importance for the success of this novel type of experiment: H. Aaser, G. Abbrugiati, P. Anzoli, R.M. Audria, J. Ballansat, G.C. Barisone, C. Benvenuti, M. Berthet, J.-C. Billy, H. Bonnefon, J.-C. Brunet, R. Calder, E. Ciapala, F. Conforti, F. Dalla Santa, G. Dughera, D. Flakowski, G. Foffano, C.B. Girard, G. Giraudo, E. Gjøtterud, C. Guillon, G. Jacquet, D. Kemp, R. Keyser, R. Kiesler, N. Madjar, P. Martucci, G. Massari, G. Maurelli, M. Moynot, P. Mugnier, R. Mundwiller, F. Nordby, E. Peschardt, C. Petit, D. Ploujoux, P. Poggi, M. Reynaud, T. Risselada, P. Sahuc, E. Sbrissa, J.-M. Schmitt and F. Verkerk. We wish to express our warm thanks to Dr. K. Potter for his help throughout the experiment, and to the ISR engineers and technicians who prepared the special machine-running conditions. The work of L. Mattera, A. Pozzo, F. Tommasini and U. Valbusa in the H_2 target system design and commissioning has been essential. We are also indebted to the staff of the Antiproton Accumulator (AA) and the Proton Synchrotron (PS) machines for their remarkable performance in the manipulations of the antiproton beam.

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