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Abstract

Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, we have obtained the first evidence for B meson decays into χ_c mesons. The inclusive branching ratio for the decay $B \to \chi_{c1}X$ was measured to be $(1.05 \pm 0.35 \pm 0.25)\%$ assuming no χ_{c2} production. In addition, four candidates for the exclusive decay $B^\pm \to \chi_{c1}K^\pm$ have been observed, corresponding to a branching ratio of $(0.19 \pm 0.13 \pm 0.06)\%$.

Production of $c\bar{c}$-states in B meson decays offers a unique opportunity for study of the interplay between the weak and strong interactions. These processes are expected to proceed through "colour-suppressed" diagrams, requiring colour matching between the c and $\bar{c}$ quarks to produce the final charmonium state [1,2,3,4]. The soft gluon high order corrections are expected to be smaller for heavy states than for light hadrons and their contribution is usually neglected [2,3]. However, this assumption does not have a firm theoretical justification [1]. According to theoretical models, J/ψ and ψ' mesons are produced by the vector current in B meson decays, while the axial vector current is responsible for transitions to η_c and χ_{c1} mesons [2,5]. An experimental study of the latter is an important complement to previous results on the J/ψ and ψ' channels, testing the various theoretical approaches. Production of the other charmonium states, χ_{c0} and χ_{c2}, in B meson decays is forbidden, if the effect of soft-gluon exchange is ignored [2,5].

A number of theoretical predictions developed for the charmonium production in B meson decays [6,7,8,9,10] have stimulated an extensive experimental study [11,12,13]. ARGUS has previously reported the observation of J/ψ and ψ' meson production in B meson decays. Here we present the first evidence of axial vector meson χ_{c1} production in B meson decays. The analysis is based on data obtained using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The data sample comprises an integrated luminosity of 246 pb^{-1} on the $\Upsilon(4S)$ resonance and 98 pb^{-1} in the nearby continuum. The number of B mesons in the sample is about 418000, assuming that the $\Upsilon(4S)$ resonance decays only to $B\overline{B}$ pairs. The ARGUS detector is a 4π spectrometer described in detail elsewhere [14].

Charged particles are identified on the basis of specific ionization in the drift chamber, time-of-flight measurements, energy deposition and shower shape in the electromagnetic calorimeter and, for muons, penetration through absorber to the muon chambers. This information is combined into an overall likelihood ratio [14] for each of the allowed particle hypotheses (e, μ, π, K and p). All hadron hypotheses for which the likelihood ratio exceeds 1% are accepted. The electron or muon hypothesis is accepted if the likelihood exceeds 70%. Only those photons with an energy deposit of more than 100 MeV in the shower counters were used for this analysis.

Multihadron events are selected by requiring a total multiplicity ($n_{ch} + n_\gamma/2$) larger than 5, where n_{ch} is the number of charged particles and n_γ is a number of photons detected in the shower counters or reconstructed as an e^+e^- conversion pair. QED and continuum backgrounds are further suppressed by requiring the second Fox-Wolfram momentum H_2 to be smaller than 0.5. Together, these requirements have a 98% efficiency for the studied process.

The search for χ_c mesons is made in the decay mode $\chi_c \rightarrow J/\psi\gamma$, where the J/ψ is reconstructed in the leptonic mode $J/\psi \rightarrow e^+e^-(\mu^+\mu^-)$. Lepton momenta are required to be larger than 0.9 GeV/c, which is the kinematical limit for leptons from J/ψ mesons produced in B meson decays. For further analysis a mass-constrained fit is applied to lepton pairs having an invariant mass within ±100 MeV/c^2 of the nominal J/ψ mass. In order to suppress faked photons due to noise in the shower counter electronics the only photons registering in at least two adjacent counters are accepted for this study. Photons which can be combined with another photon to form a pair within ±70 MeV/c^2 (about $\pm3\sigma$) of the nominal π^0 meson mass are rejected in order to suppress background from π^0 meson decays. Finally, the $J/\psi\gamma$ combinations are required to have momenta less than 1.7 GeV/c, which is the kinematic bound for χ_c production in B meson decays.

The mass spectrum for all accepted $J/\psi\gamma$ combinations is shown in fig.1a after continuum subtraction. An enhancement in the χ_c mass region is seen in this plot, while the continuum contribution is small and exhibits no enhancement in the signal region. The solid line in fig.1a represents a Monte Carlo estimate of the background normalized to the number of lepton pairs in J/ψ mass region. Background contributions to the observed signal originate from the following sources:

1. J/ψ mesons and photons from different B meson decays
2. Uncorrelated leptons with an invariant mass around J/ψ mass, combined with a photon
3. J/ψ mesons and photons produced in the decay of a single B meson

A major fraction of the background (about 80%) is due to uncorrelated combinations of photons and J/ψ mesons (1) or lepton pairs (2). This background can be reliably estimated by Monte Carlo studies because it depends only on the momentum spectra of photons, J/ψ mesons and uncorrelated leptons, which are individually well reproduced by the simulation. The simulation of background (2) has been experimentally confirmed using $e^\pm\mu^\mp\gamma$ combinations from the data (see fig.1b). The background level in the $J/\psi\gamma$ mass distribution is normalized to the total number of $\ell^-\ell^-$ pairs

observed in the J/ψ signal band. The uncertainty in the normalization is about 7%, as determined by varying the average number of photons in events with J/ψ candidates within experimental errors. A variation of the photon energy spectrum, or the relative fraction of backgrounds (1) and (2), leads to much smaller changes.

Since the continuum contribution is small the uncorrelated background before the anti-π^0 cut can be also estimated by mixing photons and lepton pairs from different events with J/ψ candidates. The result is in very good agreement with the Monte Carlo estimate of this background.

The correlated background (3) is found to be small (about 19% of the total), and moreover is smoothly behaved as a function of $J/\psi\gamma$ invariant mass. This estimate is obtained from Monte Carlo. Monte Carlo is adjusted to the data using the measured branching ratios of the exclusive B meson decays into J/ψ mesons and inclusive momentum spectra of J/ψ and photon. The Monte Carlo estimate is also tested using data by comparing the average neutral multiplicity in the $B\overline{B}$ events and in the events containing J/ψ mesons. Over the χ_c mass region the correlated background changes by less than 4% if the momentum spectrum of J/ψ meson is varied within experimental errors. The total uncertainty in the background normalization in the χ_c mass region is 8%.

As demonstrated in fig.1a, the $J/\psi\gamma$ invariant mass distribution outside the χ_c region is well described by the calculated background. After background subtraction the $J/\psi\gamma$ invariant mass spectrum is fitted with a sum of two Gaussians describing contributions from χ_{c1} and χ_{c2} mesons. Since the branching ratio for $\chi_{c0} \rightarrow J/\psi\gamma$ is only (0.66 ± 0.18)% the contribution from χ_{c0} mesons is neglected. The parameters of these Gaussians are fixed using Monte Carlo calculations to $M_{\chi_{c1}} = 3510.6$ MeV/c^2, $M_{\chi_{c2}} = 3556.3$ MeV/c^2 and $\sigma = 56$ MeV/c^2. The relative fraction of χ_{c1} and χ_{c2} contributions is left free. The fit gives 33 ± 11 events in the signal and the fraction of χ_{c1} contribution close to 100% (98^{+2}_{-60}%). Although the χ_{c2} fraction in the signal is close to 0% (2^{+60}_{-2}%) the χ_{c2} contribution can not be excluded due to the large errors. However, since theoretical models predict a suppression of χ_{c2} production in B meson decays [2,5], and the branching ratio for $\chi_{c2} \rightarrow J/\psi\gamma$ is one-half of that for $\chi_{c1} \rightarrow J/\psi\gamma$, we assume no contribution to the signal from χ_{c2} production, and attribute the excess to χ_{c1} production. Fitting the signal with a single Gaussian describing χ_{c1} contribution ($M = 3510.6$ MeV/c^2, $\sigma = 56$ MeV/c^2) we obtain 33 ± 11 events. Thus the number of events in the signal does not practically change if only χ_{c1} production is taken into account.

A detailed Monte Carlo simulation was performed to determine the detector acceptance. The efficiency for the decay mode $\chi_{c1} \rightarrow J/\psi\gamma$ is found to be essentially independent of χ_{c1} momentum, with an average value of $(20 \pm 2)\%$. Using $Br(\chi_{c1} \to J/\psi\gamma) = (27.3 \pm 1.6)\%$ and $Br(J/\psi \to e^+e^-(\mu^+\mu^-)) = (6.9 \pm 0.9)\%$ [15], and assuming that all χ_{c1} are produced in B meson decays, we obtain $Br(B \to \chi_{c1}X) = (1.05 \pm 0.35 \pm 0.25)\%$. The systematic error includes contributions from the uncertainties on the χ_{c1} and J/ψ branching ratios, background estimation, predicted widths, efficiency calculation and the number of B mesons. The measured branching ratio of the $B \to \chi_{c1}X$ decay is higher than theoretical prediction by about a factor of 4 [5]. Such a large branching ratio means that about $(30 \pm 10)\%$ of J/ψ mesons in $\Upsilon(4S)$ decays come from the decay $\chi_{c1} \to J/\psi\gamma$.

An important cross-check for this result on χ_{c1} production can be performed by studing J/ψ combinations with photons converted in the material in front of the main drift chamber. The reconstruction of converted photons, γ_c, proceeds by finding a secondary vertex formed by an e^+e^- pair with invariant mass smaller than 10 MeV/c^2. For this analysis, a requirement of 1% or more was made on the likelihood ratio for the electron hypothesis for the e^+ and e^- candidates. The probability to observe a converted photon from $\chi_c \to J/\psi\gamma$ decay is about 50 times smaller than the efficiency for photon detection in the electromagnetic calorimeter and it is even smaller for the lower photon energies, but the energy resolution is an order of magnitude better. Thus, the signal width for $J/\psi\gamma_c$ combinations from χ_c decays is expected to be $\sigma = ^{+5}_{-8}$ MeV/c^2.

Converted photons from π^0 decays are suppressed in analogy to the previous analysis by requiring that the invariant mass of the γ_c with any other photon in the event should be more than 40 MeV/c^2 (about 3σ) away from the π^0 mass. Only four $J/\psi\gamma_c$ combinations with momenta less than 1.7 GeV/c remained after this requirement in the whole invariant mass range. Two of them, with masses 3505 and 3496 MeV/c^2, are within $\pm 2\sigma$ of the χ_{c1} mass. The background in this region can be reliably estimated using the observed $J/\psi\gamma$ invariant mass spectrum, folded with the probability for photon conversion measured experimentally using data on photon production. By this means, the expected background in the χ_{c1} mass region is determined to be 0.16 ± 0.03 events. The probability of observing 2 or more events as a result of a background fluctuation is about 1%. Using the result of the previous analysis, the number of χ_{c1} decays to J/ψ and converted photon is expected to be 0.6 ± 0.2 events.

A search for exclusive decays of $B^{\pm}$ mesons into $\chi_{c1}K^{\pm}$ has also been performed. The J/ψ mesons were reconstructed, as in the previous analysis, in their leptonic decay modes. A mass-constrained fit is applied for $\ell^+\ell^-$ pairs having an invariant mass within ± 100 MeV/c^2 of the nominal J/ψ mass. These J/ψ candidates are then

combined with photons and a mass-constrained fit is performed for all combinations having an invariant mass within ± 120MeV/c^2 of the χ_{c1} mass. For converted photons this mass interval is asymmetric: $^{+10}_{-16}$ MeV/c^2. The energy of B mesons from $\Upsilon(4S)$ decays should be equal to the beam energy. Therefore, B meson candidates are formed from $\chi_{c1}K^{\pm}$ combinations having an energy within three standard deviations of the beam energy. A kinematic fit is then applied to the B candidates, constraining their energy to the beam energy. This fit improves the mass resolution by an order of magnitude to about 5 MeV/c^2. To avoid multiple counting, only one candidate per event is accepted, by choosing the candidate with the highest total probability calculated for the sum of all χ^2 contributions from kinematic fits and particle identification. Only candidates with the total probability larger than 1% are accepted.

The resulting $\chi_{c1}K^{\pm}$ mass spectrum is shown in fig.2. There are four events in the B meson mass range $M(\chi_{c1}K^{\pm}) > 5270$ MeV/c^2. The same procedure applied to $J/\psi\gamma$ candidates from the left (3271 ± 120 MeV/c^2) and right (3751 ± 120 MeV/c^2) sidebands of χ_{c1} finds only one event in the B mass range. The same analysis is performed for continuum data taken just below Υ(4S) resonance. No candidates with a mass larger than 5170 MeV/c^2 are found in either the $\chi_{c1}K^{\pm}$ combinations or in the case of χ_{c1} side bands. From this we estimate the continuum background in the B meson mass region to be less than 0.1 event. A major fraction of the background (about 60%) is due to random combinations of $J/\psi K^{\pm}$ pairs produced in the decay of one B meson (mainly from $J/\psi K\pi$ mode) and photons originating from another B meson. The expected background contribution from all sources is estimated using Monte Carlo studies to be 1.1 ± 0.3 events. The error is determined by varying the branching ratios for exclusive B meson decays with $J/\psi K(n\pi)$ in the final state within the experimentally allowed limits. The main contribution to the error comes from the uncertainty of the branching ratios for $B \to J/\psi K^{\pm}\pi$. The probability to observe 4 or more events as a result of a background fluctuation is less than 3%.

A detailed Monte Carlo simulation was performed to determine the detector acceptance. The efficiency for the decay $B^{\pm} \to \chi_{c1}K^{\pm}$ is found to be $(20 \pm 2)\%$. This leads to $Br(B^{\mp} \to \chi_{c1}K^{\mp}) = (0.19 \pm 0.13 \pm 0.06)\%$ assuming that 50% of all $\Upsilon(4S)$ mesons decay into B^+B^- pairs. The systematic error comes from the uncertainties of χ_{c1} and J/ψ branching ratios and the background estimation.

In conclusion, we have obtained the first evidence for χ_c meson production in $\Upsilon(4S)$ decays. A signal of 33 ± 11 events containing the decays $\chi_c \to J/\psi\gamma$ is observed for χ_c momenta below the kinematic limit for B decays. Assuming that $\Upsilon(4S)$

mesons decay only to $B\overline{B}$ pairs, and neglecting possible χ_{c2} production, a branching ratio of $(1.05 \pm 0.35 \pm 0.25)\%$ is obtained for $B \to \chi_{c1} X$. This result is a factor of 4 larger than theoretical prediction. The branching ratio for $B^{\mp} \to \chi_{c1} K^{\mp}$ decay has been determined to be $(0.19 \pm 0.13 \pm 0.06)\%$, assuming $Br(\Upsilon(4S) \to B^{+}B^{-}) = 50\%$. Such a large branching ratio implies that the analogous decay $B^0 \to \chi_{c1} K_s^0$ could be useful in future searches for CP violation in B decays.

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Figure Captions

Figure 1: Invariant mass distribution of $\ell^+\ell^-\gamma$ combinations after continuum subtraction, where the $\ell^+\ell^-$ pair has been fitted to the mass of the J/ψ meson. (a) e^+e^- and $\mu^+\mu^-$ combinations from direct $\Upsilon(4S)$ decays (points) and nearby continuum (histogram), the solid line shows the expected background, (b) $e^\pm\mu^\mp$ combinations from direct $\Upsilon(4S)$ decays (points) compared with Monte Carlo calculation (solid line).

Figure 2: Invariant mass distribution of $\chi_{c1}K^\pm$ combinations after the energy constrained fit. The solid line shows the expected background.

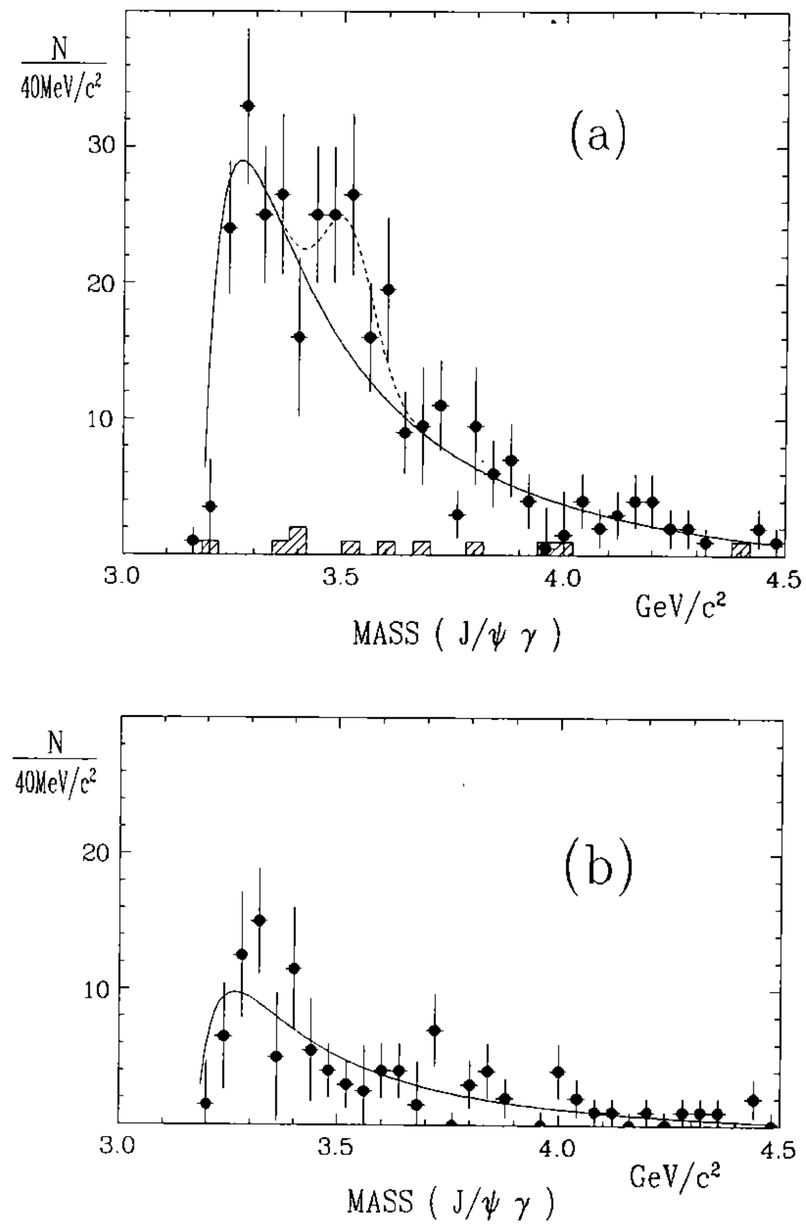

Figure 1

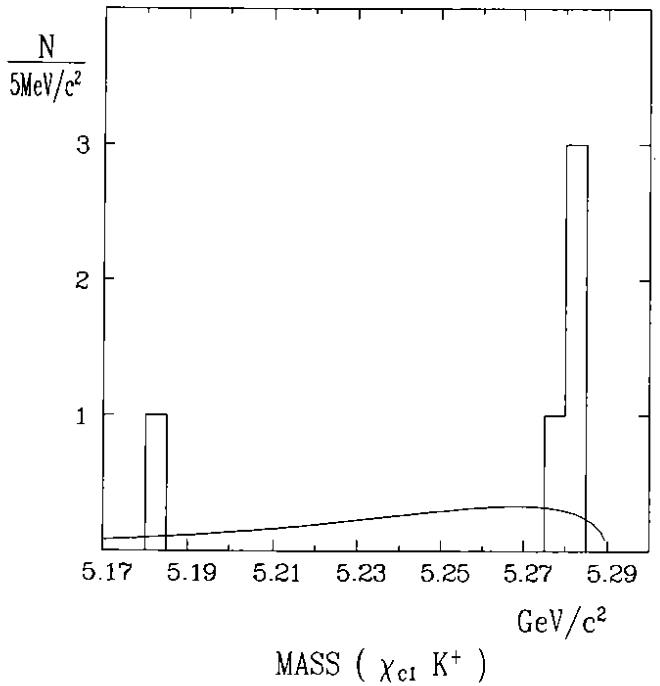

Figure 2.