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Observation of J/ψ Production in Multihadronic Z^0 Decays

The OPAL Collaboration

Abstract

The production of J/ψ mesons in multihadronic Z^0 decays has been observed in the e^+e^- and $\mu^+\mu^-$ final states. From a sample of approximately 45 reconstructed J/ψ mesons, the inclusive branching fraction is measured to be

$$Br(Z^0 \rightarrow J/\psi + X) = (4.5 \pm 0.8 \pm 0.4 \pm 0.6) \times 10^{-3},$$

where the first error is statistical, the second systematic, and the third error is due to the uncertainty in the leptonic decay rate of the J/ψ . The J/ψ energy distribution is consistent with the distribution expected from B hadron decays. The average B hadron lifetime is calculated from the measured distances between the primary and J/ψ vertices, resulting in

$$\tau_B = 1.32^{+0.31}_{-0.25} \pm 0.15 \text{ psec},$$

where the first error is statistical and the second systematic.

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1 Introduction

Over a decade ago, it was proposed [1] that events containing J/ψ mesons are well suited to tag B decays, reconstruct exclusive decay modes, and measure the lifetimes of the various B hadrons individually. Due to the substantial branching fraction of Z^0 decays into $b\bar{b}$ pairs ($\approx 15\%$) and the high cross section at the Z^0 peak, these subjects can be studied at LEP. Even in events with a high particle multiplicity, J/ψ mesons can be efficiently identified by their decays into lepton pairs. With the present number of Z^0 decays collected at LEP, the assumption that J/ψ mesons arise predominantly from primary B hadron decays can be tested. In particular, a contribution due to J/ψ production from gluons is predicted [2, 3]. The fraction of J/ψ mesons produced in exclusive Z^0 decays or photon-photon collisions is predicted [4] to be small.

The average B hadron decay length of about 2.3 mm is sufficiently long to measure the lifetime of hadrons containing b quarks by determining the distance between the primary vertex and the vertex formed by the J/ψ . Using high resolution vertex detectors, the position of the decay vertex can be measured with an error that is small compared to the particle decay length.

Presented here is an analysis of data recorded with the OPAL detector at the CERN e^+e^- collider LEP at a luminosity-weighted average energy of 91.31 GeV. J/ψ mesons are reconstructed from their decays into lepton pairs selected from a data sample of approximately 163,000 identified [5] multihadronic Z^0 decays, corresponding to an integrated luminosity of about 7.7 pb^{-1} . The measurement of the inclusive J/ψ production rate and the determination of the average B hadron lifetime, extracted by a maximum likelihood fit to the measured decay lengths, is presented.

2 The OPAL detector

The OPAL detector is described in detail elsewhere [6]. The features relevant to this analysis are described below.

Charged tracking is provided by the central detector, consisting of the vertex, jet, and z-chambers. The vertex chamber, containing 36 azimuthal¹ sectors of 18 sense wires, and the jet chamber, containing 24 sectors of 159 sense wires, are used to measure the momentum of charged particles. The combination of these chambers leads to $\sigma(p_T)/p_T = \sqrt{0.02^2 + (0.0018 \cdot p_T)^2}$, where p_T is the momentum transverse to the beam direction in units of GeV/c.

The polar angle of the track is determined in the jet chamber using the information from charge division on each of the wires and from stereo wires in the vertex chamber. Within the acceptance of the z-chambers ($|\cos\theta| < 0.725$), a precise determination of the polar track angle is available with an efficiency of about 83%. The ionization measurements from the jet chamber are used to calculate the mean energy loss, $dE/dx|_{\text{mean}}$, of particles traversing the chamber gas. In multihadronic events, the $dE/dx|_{\text{mean}}$ resolution is about 3.8 %, equivalent to a 2σ separation between pions and kaons up to 13 GeV/c.

¹The coordinate system is defined with positive z along the outgoing e^- beam direction, θ and ϕ being the azimuthal and polar angles.

The electromagnetic calorimeter contains a barrel ($|\cos \theta| < 0.82$) and two annular endcaps ($0.81 < |\cos \theta| < 0.98$). The barrel electromagnetic calorimeter consists of a cylindrical array of 9440 lead glass blocks of $24.5 X_0$ thickness that point approximately to the interaction region. The endcap electromagnetic calorimeter consists of 2264 lead glass blocks of $20 X_0$ thickness, projecting along the beam axis. For 10 GeV/c electrons, the position resolution is about 4 mrad (3.5 mrad) in the polar angle and about 5 mrad (3.5 mrad) in the azimuthal angle for the barrel (endcap) calorimeter.

In between the coil, which provides a magnetic field of about 0.43 T, and the barrel lead glass shower counter, the barrel presampler detector is installed. The detector consists of two cylindrical layers of limited streamer tubes with wires parallel to the beam axis. The presampler provides a measurement of the shower development following about $2/\sin \theta X_0$ of material, and has a spatial resolution of better than 2 (3) mrad in azimuthal and polar angles for minimum ionizing particles (showers). In the space between the central detector pressure vessel and the endcap electromagnetic calorimeter, a presampler detector [7], built of high gain multiwire proportional chambers is installed in an umbrella-like arrangement. This presampler provides a measurement of the shower development following roughly $1.6 X_0$ of material, and has a position resolution of about 8 mrad in azimuth and about 2.0 (4.5) mrad in polar angle for minimum ionizing particles (showers), in the angular range $0.83 < |\cos \theta| < 0.95$.

The barrel and endcap muon chambers, together with the hadron calorimeter, form the muon identification system, which covers polar angles in the range $|\cos \theta| < 0.98$. The barrel region of the muon chambers, covering the region $|\cos \theta| < 0.68$, consists of four layers of planar drift chambers, providing measurements in the (r, ϕ) plane. Information on the polar angle of the muon track is available with a resolution of about 4 mrad at 45 GeV/c for 74% of all muons. The endcap region, $0.60 < |\cos \theta| < 0.98$, is covered by four layers of limited streamer tubes, each layer measuring in the (x, z) and (y, z) planes. The spatial resolution in each of the coordinates is between 1 and 2 mrad for 45 GeV tracks. The hadron calorimeter, which consists of 9 (8) layers of streamer tubes interleaved with iron slabs of the magnet return yoke in the barrel (endcap), is read out via 4 mm wide strips and projective towers formed from $50 \times 50 \text{ cm}^2$ pads. The strips provide measurements in the (r, ϕ) plane. The minimum momentum required for a muon to penetrate to the muon chambers varies between 2.2 and 3.0 GeV/c, depending on the polar angle. Muons above 1.6 GeV/c are tracked in the hadron calorimeter.

3 The selection of J/ψ candidate events

Tracks used in this analysis have to satisfy the requirements $p_T > 0.1 \text{ GeV}/c$, $|d_0| < 2.5 \text{ cm}$, and $|z_0| < 50 \text{ cm}$, where $|d_0|$ is the distance of closest approach to the interaction point in the plane perpendicular to the beam axis and z_0 is the z -value of the track at this point.

The number of hits in the jet chamber, associated to the charged track, has to exceed 20, corresponding to $|\cos \theta| < 0.97$. It is further required that the track contain more than 50% of the hits expected for its polar angle. In order to improve the polar angle determination of the tracks all lepton candidate tracks are constrained to the event vertex along the beam direction, which is known with 0.5 mm accuracy.

Electromagnetic clusters consist of groups of contiguous lead glass blocks, with a minimum energy of 0.15 GeV. Endcap clusters are required to contain a minimum of two adjacent blocks.

Muon track segments are reconstructed either in the hadron calorimeter or the muon chambers. A hadron calorimeter track segment is considered, if at least four layers have aligned clusters with at least one cluster in the outer four layers or with an associated hit in the muon chambers.

The selection of events with J/ψ candidates proceeds as follows.

J/ψ candidate tracks are required to belong to the same event hemisphere, as defined by the thrust axis, and to the same jet, where the LUND clustering algorithm [8] is used to group charged tracks into jets. According to the Monte Carlo, the last requirement eliminates about 4% of J/ψ mesons produced in B hadron decays, predominantly at low J/ψ momentum. This kinematic requirement reduces the background significantly at larger invariant masses of the two particle system.

In order to guarantee a sufficiently good momentum resolution, the polar angles of the J/ψ candidate tracks are restricted to be within $|\cos \theta| < 0.9$. As a cross check, an analysis restricted to the barrel region ($|\cos \theta| < 0.72$), demanding that both tracks have associated z -chamber track segments to ensure optimal polar angle resolution, has also been pursued. Consistent results have been obtained.

For the $J/\psi \rightarrow \mu^+\mu^-$ search, candidate events are required to contain at least two muon segments as defined above, both associated to charged tracks with momenta above 1.9 GeV/ c (selection I). The corresponding muon identification efficiency for $|\cos \theta| < 0.72$ is about 83% at 2 GeV/ c and about 96% above 3.5 GeV/ c . In order to study systematic effects, other μ -identification criteria are used that suppress the background from misidentified hadrons further. In the lifetime analysis, the following additional requirements are introduced (selection II). For segments identified only in the hadron calorimeter, it is required that at least one associated hit in the muon chambers be found if the track falls within the muon chamber acceptance and the momentum exceeds 2.4 GeV/ c . In addition, at least one of the two tracks must be associated with a hadron calorimeter *and* a muon chamber segment if at least one of the tracks is within the combined acceptance of the two detector elements. Since the Monte Carlo predicts that a significant fraction of the background events with misidentified hadrons contains kaons or protons, it is further required that the $dE/dx|_{mean}$ measurement for tracks associated with the J/ψ have at least a 1% probability to be consistent with the expectation for muons. This condition is applied only if at least 60 dE/dx samples contribute to the measurement.

In order to improve the polar angle determination of muon candidate tracks without associated z -chamber track segments, the position information from the barrel presampler and muon counters is used in the tracking. The mass spectra for opposite- and equal-sign muon candidate pairs are shown in Fig. 1.

For the $J/\psi \rightarrow e^+e^-$ search, candidate tracks are required to have momenta above 1.5 GeV/ c . Tracks with a polar angle in the range $0.75 < |\cos \theta| < 0.82$ are excluded from the analysis because the electromagnetic energy measurement in this angular region is significantly degraded by the material of the central detector pressure vessel (roughly $4 X_0$) in front of the lead glass shower counters.

In order to be declared consistent with an electron, tracks must have more than 20 associated dE/dx samples with $dE/dx|_{mean} > 8.5$ keV/cm. For $8.5 \text{ keV/cm} < dE/dx|_{mean} < 10 \text{ keV/cm}$, the probability for the electron hypothesis has to exceed 2%. The combined efficiency of these requirements is $(90.5 \pm 2.0)\%$ for electron tracks. It is further required² that $0.75 < E/p < 1.3$, where E is the energy in the lead glass calorimeter associated to the charged track with momentum p . The lower cut is satisfied by $(95.5 \pm 0.5)\%$ of the electrons. The upper cut suppresses a tail towards low invariant masses in the J/ψ peak, which is due to radiation in the material of the detector. The overlap of electron clusters from the J/ψ with other showers might be expected to cause a significant inefficiency in this cut. However, since the leptons from the J/ψ decay are, in general, well isolated, the cut is passed by $(94.1 \pm 1.6)\%$ of the signal events in the invariant mass region between 2.85 and 3.30 GeV/ c^2 .

For tracks in the barrel region with associated z -chamber hits, whose position at the surface of the shower counter is very well determined, the small lateral size of electromagnetic electron showers can be used to suppress backgrounds from overlapping tracks and photon showers. It is required that $E_{cone}/p > 0.6$, where E_{cone} is the energy in a cone of 30 mrad about the charged track. The efficiency of this cut is $(98.7 \pm 0.3)\%$. For tracks without associated z -chamber track segments the associated clusters must contain 90% of the total cluster energy in at most four lead glass blocks.

The Monte Carlo predicts that the contribution of electrons from photon conversions to the di-electron sample is approximately 3% in the invariant mass region between 2.0 and 4.0 GeV/ c^2 . Electrons associated with a vertex consistent with a photon conversion are excluded from the sample with an efficiency of roughly 50%.

In order to improve the polar angle determination of electron candidate tracks without associated z -chamber track segments, the position information from the presampler and the electromagnetic calorimeter is included in the tracking. The mass spectra for opposite- and equal-sign electron candidate pairs are shown in Fig. 2.

4 Background estimate

The background underneath the J/ψ signal is estimated from:

- a sample of 187538 $Z^0 \rightarrow q\bar{q}$ JETSET V7.2 Monte Carlo events [8, 9] with a full simulation of the OPAL detector [10],
- a fit to the invariant mass spectrum, and from
- the invariant mass distribution of lepton pairs with equal charges.

The number of background events obtained from the Monte Carlo is corrected for efficiency differences between data and Monte Carlo, in particular for the lepton misidentification probability for hadrons. The semileptonic branching fractions³ $Br(c \rightarrow \ell^+ X) = 0.079 \pm 0.009$ [11],

²For isolated 10 GeV/ c electron tracks, the resolution in E/p is approximately 8% in the barrel and 9% in the endcap.

³Throughout the paper, charge conjugate decays for anti-quarks are also implied.

$Br(b \rightarrow \ell^- X) = 0.115 \pm 0.009$ [12], and $Br(b \rightarrow c \rightarrow \ell^+ X) + Br(b \rightarrow \bar{c} \rightarrow \ell^- X) = 0.102 \pm 0.012$ [13] are assumed, where $\ell^\pm$ denotes electrons or muons. As can be seen from Figs. 1 and 2, the shape and the number of background events for pairs with equal and opposite charges are well predicted by the Monte Carlo.

The background to the J/ψ signal coming from events containing two leptons is predominantly due to $Z^0 \rightarrow b\bar{b}$ events, where the b quark decays into a lepton $b \rightarrow \ell^- X$ and the second lepton stems from the cascade decay $b \rightarrow c \rightarrow \ell^+ X$, giving opposite-sign leptons. This is also evident from the mass spectra for equal-sign leptons, where the background from two leptons is very low.

The background to the J/ψ signal from events containing one misidentified lepton stems mainly from heavy quark decays. A large fraction of the misidentified leptons are B or D hadron decay products.

The background from two misidentified leptons, which is significant only for the $\mu^+\mu^-$ final state, contains a substantial fraction of kaons and protons (approximately 65%). This background is suppressed by the $dE/dx|_{mean}$ requirement in selection II.

The background fractions of different background sources, estimated using the Monte Carlo, are listed in Table 1 for the sample of opposite-sign leptons.

5 The inclusive J/ψ branching fraction

In order to determine the efficiency for detecting leptonic J/ψ decays, a Monte Carlo simulation of the decay chain $Z^0 \rightarrow b\bar{b}$ with $b, \bar{b} \rightarrow J/\psi + X$ is used. The Monte Carlo is based on the JETSET V7.2 [8] generator with full detector simulation [10]; b quarks are fragmented according to the Peterson *et al.* fragmentation scheme [15] with the fragmentation parameter $\epsilon_b = 0.0055$. For the representation of weak bottom and charm hadron decays, the decay tables of EURODEC [14] are implemented in the Monte Carlo.

The number of events containing J/ψ mesons is determined by

- counting the number of signal events in the invariant mass region between 2.95 and 3.30 GeV/c^2 (2.85 and 3.30 GeV/c^2) of $\mu^+\mu^-$ (e^+e^-) pairs above the background predicted by the Monte Carlo, and by
- performing fits to background and signal.

The number of signal and background events in the signal regions are listed in Table 1 together with the respective detection efficiencies. In order to study a possible systematic dependence on the number of predicted background events, the branching ratio has also been determined for several other sets of lepton identification cuts, giving consistent results.

Several fits to the di-lepton mass spectra using different fitting functions and various fitting intervals have been made.

In the $\mu^+\mu^-$ case, a polynomial of order two, an exponential function, and a background form obtained from the Monte Carlo have been used to describe the background. A Gaussian has been used to model the signal shape. The measured mass and widths are 3.080 ± 0.018 GeV/ c^2 and 0.062 ± 0.014 GeV/ c^2 , respectively. The mass is consistent with the nominal J/ψ mass of 3.097 GeV/ c^2 . The observation, that the width is lower than the Monte Carlo expectation of 0.088 ± 0.004 GeV/ c^2 , has been taken into account in the systematic error on the branching ratio (7%). Fig. 1 (a) shows the $\mu^+\mu^-$ mass spectrum with a fit to a Gaussian and a background shape determined from the Monte Carlo. For this fit, the normalization of the background is within $(10 \pm 17)\%$ of the absolute Monte Carlo prediction.

In the e^+e^- case, background and signal shapes have been derived from the Monte Carlo, to take into account the asymmetric signal shape due to external photon radiation. To allow for a possible systematic shift in the peak mass position of the data, the peak mass value has been varied by ± 0.030 GeV/ c^2 . The effective mass of the signal, if fitted by a Gaussian, is 3.088 ± 0.034 GeV/ c^2 , which is consistent with the Monte Carlo expectation of 3.086 ± 0.007 GeV/ c^2 . Fig. 2 (a) shows the fit to the e^+e^- mass spectrum; the normalization of the background is within $(4 \pm 17)\%$ of the value predicted by the Monte Carlo.

The branching ratio is calculated according to the formula

$$Br(Z^0 \rightarrow J/\psi + X) = \frac{\text{no. of signal events}}{\text{no. of } Z^0 \rightarrow \text{hadron events} \cdot \frac{\Gamma_Z}{\Gamma_{\text{HAD}}}} \cdot \frac{\eta_{\text{HAD}}}{\eta_{J/\psi}} \cdot \frac{1}{Br(J/\psi \rightarrow \ell^+\ell^-)},$$

with [5] $\Gamma_{\text{HAD}} = 1.739 \pm 0.017$ GeV, $\Gamma_Z = 2.492 \pm 0.016$ GeV, $\eta_{\text{HAD}} = 0.986 \pm 0.004$, and [11] $Br(J/\psi \rightarrow \ell^+\ell^-) = 0.069 \pm 0.009$. The efficiencies of the multihadron and J/ψ selections are denoted as η_{HAD} and $\eta_{J/\psi}$, respectively.

Averaging the results from the counting and fitting methods used to determine the number of J/ψ events, the following values are obtained:

$$\begin{aligned} Br(Z^0 \rightarrow J/\psi + X) &= (5.0 \pm 1.1 \pm 0.6 \pm 0.7) \times 10^{-3} & (\mu^+\mu^- \text{ final state}) \\ &= (3.9 \pm 1.3 \pm 0.5 \pm 0.5) \times 10^{-3} & (e^+e^- \text{ final state}). \end{aligned}$$

The first error is statistical, the second error is estimated from varying the fitting functions, fitting intervals and selection cuts, and the third error is due to the error on the $J/\psi \rightarrow \ell^+\ell^-$ branching fraction. The results from both leptonic decay modes are combined by forming a weighted average, giving the value of

$$Br(Z^0 \rightarrow J/\psi + X) = (4.5 \pm 0.8 \pm 0.4 \pm 0.6) \times 10^{-3}.$$

Fig. 3 (b) shows the background subtracted and efficiency corrected x_E distribution for the J/ψ candidates from the combined data sample, where x_E is the ratio of the energy of the J/ψ meson to the beam energy. As can be seen from Fig. 3 (a), the efficiency decreases towards lower values of x_E due to the low momentum cut-off and the requirement that the two leptons be contained in the same jet. The x_E -distribution is compared to the distribution predicted by the EURODEC Monte Carlo (dashed histogram) for J/ψ mesons from B decays, assuming that all B hadrons decay with the same branching ratio $Br(B \rightarrow J/\psi + X) = (1.12 \pm 0.15 \pm 0.15)\%$ [16]. The prediction of Ref. [3] for J/ψ production through the $g^* \rightarrow J/\psi g g$ and $g^* \rightarrow b\bar{b} \rightarrow J/\psi X$ processes is shown by the shaded band.

6 A determination of the average B hadron lifetime τ_B

A vertex is reconstructed in the (r, ϕ) plane from the intersection of the lepton tracks. For the primary vertex position, the centroid of the beam spot, determined over the period of a LEP fill, is taken. The transverse dimensions of the beam ellipse are $160 \mu\text{m}$ by $8 \mu\text{m}$. The best estimate of the decay length l_{xy} between primary and di-lepton vertex is determined in the (r, ϕ) plane along the lines described in Ref. [17]. In this method, the most probable decay and production points are calculated, subject to a directional constraint, from the known beam and vertex positions and corresponding errors. As an estimate of the direction of the parent B hadron the direction of the closest jet, as defined above, is taken, which coincides with the true B hadron flight path to within 40 mrad . The three dimensional decay length $l_{xyz} = l_{xy} / \sin \theta$ is determined using the polar angle θ of the closest jet.

J/ψ candidates from the $\mu^+\mu^-$ and e^+e^- channels are selected if the di-lepton invariant mass is in the signal regions $2.95\text{-}3.30 \text{ GeV}/c^2$ and $2.85\text{-}3.30 \text{ GeV}/c^2$, respectively.

Different lepton identification criteria are employed to study a possible systematic dependence of the lifetime measurement on the fraction and type of background events. Table 1 shows the number of events and percentage of background events estimated by the Monte Carlo for three of the selections considered. The decay length distribution from the combined samples of the $\mu^+\mu^-$ (selection II) and e^+e^- channels is shown in Fig. 4. The mean of the distribution is clearly offset from zero and the distribution exhibits a tail towards long decay lengths.

The errors on the decay lengths vary widely, in particular since the tracks are not required to have associated vertex chamber hits. Therefore a maximum likelihood fit is used to fully exploit the available information. Using tracks that come from the primary event vertex, it has been verified that the calculated error on the decay length gives a good description of the true error.

In the maximum likelihood fit, the decay time t of B hadrons is parametrized by a convolution of an exponential and a normal distribution. The distribution function of the decay length $l_{xyz} = p_B/m_B \cdot t$ is calculated assuming an average B hadron mass m_B between 5.30 and $5.35 \text{ GeV}/c^2$.

The momentum p_B of the parent is not known, but can be estimated by convoluting the measured J/ψ momentum with the probability distribution of $p_B/p_{J/\psi}$ taken from the Monte Carlo. In this way the sensitivity to the assumed shape of the B fragmentation function is much reduced. The changes in the measured lifetime due to a variation of $\epsilon_b = 0.006 \pm 0.004$ in the bounds given by the LEP experiments [18] are negligible.

The background is treated in the maximum likelihood fit as follows. The effective lifetimes associated with background events with zero, one, or two misidentified leptons have been determined using Monte Carlo events as $(1.0^{+0.4}_{-0.2}) \cdot \tau_B$, $(0.95 \pm 0.20) \cdot \tau_B$, and $(0.1 \pm 0.3) \cdot \tau_B$, respectively. For the purpose of simplicity, the same momentum distributions as for the signal sample have been assumed. The background contributions are estimated from the Monte Carlo (see Table 1).

Track reconstruction problems, bremsstrahlung in the material of the detector, large angle

multiple scattering, or backgrounds from decays or photon conversions, can all lead to abnormally long decay lengths. These effects, which are determined to occur at the level of a few percent⁴, are included in the maximum likelihood fit by a term with constant probability in the range -3.0 cm to 3.0 cm. The assumed fraction of these events is $(3^{+7}_{-2})\%$.

J/ψ mesons from sources other than primary b quark decays are assumed to originate at the primary vertex and are represented by a Gaussian probability distribution in the maximum likelihood fit. The fraction of these events is taken to be $(2.2^{+2.2}_{-1.1})\%$, assuming a factor of two uncertainty in the prediction of Ref. [3].

The maximum likelihood fit is applied separately to the e^+e^- and $\mu^+\mu^-$ samples as well as to the combined set of data. The result of the fit to the combined sample is shown in Fig. 4.

Several studies have been made to estimate the systematic error on the lifetime determination, including scaling of the decay length error by $\pm 20\%$ (A) and varying the lepton identification cuts (B), the fraction of wrongly reconstructed vertices (C), and the assumed background from J/ψ mesons produced in the parton shower (D). The assumed backgrounds of events with zero (E), one (F), and two (G) misidentified leptons have been changed within 2σ of the values predicted by the Monte Carlo, while simultaneously varying the effective lifetimes associated with these backgrounds within the bounds given above. The contributions of the different error sources for the combined $\mu^+\mu^-$ and e^+e^- samples are listed in Table 2.

It has also been checked that the lifetime assumed in the Monte Carlo generator is reproduced by the maximum likelihood method applied to the tracks after detector simulation. It has been verified that estimating the original B hadron momentum and direction from the J/ψ momentum and the closest jet direction, respectively, has a negligible effect on the lifetime measurement.

The average B hadron lifetime is determined to be

$$\begin{aligned}\tau_B &= 1.34^{+0.45}_{-0.32}{}^{+0.12}_{-0.15} \text{ psec} && (e^+e^- \text{ channel}) \\ &= 1.31^{+0.48}_{-0.35}{}^{+0.16}_{-0.26} \text{ psec} && (\mu^+\mu^- \text{ channel}) \\ &= 1.32^{+0.31}_{-0.25}{}^{+0.15}_{-0.15} \text{ psec} && (\text{combined result}),\end{aligned}$$

where the first error is statistical and the second systematic. The results from the two lepton channels are in good agreement. The bigger systematic error associated to the $\mu^+\mu^-$ channel is due to two events with decay lengths of larger than 2 cm that significantly influence the result. This is mainly reflected in a larger contribution of error sources (A) and (C) to the systematic error.

7 Conclusion

In summary, the production of J/ψ mesons in multihadronic Z^0 decays has been observed in the $\mu^+\mu^-$ and e^+e^- decay channels.

⁴This fraction has been estimated in a study of the distribution of negative decay lengths using a di-lepton sample in multihadronic events and from the probability that jet chamber and vertex detector track segments are incorrectly associated due to the finite tracking resolution.

Taking the weighted average of the results from both leptonic decay modes, the inclusive branching fraction

$$Br(Z^0 \rightarrow J/\psi + X) = (4.5 \pm 0.8 \pm 0.4 \pm 0.6) \times 10^{-3}$$

has been determined. The x_E -distribution of the observed J/ψ mesons is roughly symmetric around $x_E \approx 0.5$. This is expected for J/ψ mesons from primary B hadron decays where the J/ψ mesons carry a substantial fraction of the energy of the b-quarks.

The experimentally determined branching ratio value may be compared with a prediction based on the assumption that all B hadrons decay with the same branching ratio $Br(B \rightarrow J/\psi + X) = (1.12 \pm 0.15 \pm 0.15)\%$ [16]. With this value, the theoretical prediction is

$$Br(Z^0 \rightarrow J/\psi + X) = (3.40 \pm 0.45 \pm 0.45) \times 10^{-3},$$

assuming the standard model value $Br(Z^0 \rightarrow b\bar{b}) = 0.151$. The second error is due to the uncertainty in the leptonic branching ratio of the J/ψ . The ratio of measured and theoretically predicted branching fraction, $R = 1.32 \pm 0.32$, does not depend on $Br(J/\psi \rightarrow \ell^+\ell^-)$.

Assuming, as predicted [3], that the J/ψ mesons are predominantly decay products of B hadrons, the average B hadron lifetime of

$$\tau_B = 1.32^{+0.31}_{-0.25} \pm 0.15 \text{ psec}$$

is obtained, where the first error is statistical and the second systematic. This value, which is based on approximately 36 J/ψ vertices, is in good agreement with previous measurements [19].

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Table 1: Monte Carlo estimates for backgrounds in the 2.95-3.30 GeV/c² (2.85-3.30 GeV/c²) invariant mass regions of $\mu^+\mu^-$ (e^+e^-) pairs.

Selection	number of events	efficiency [%]	background [%]		
			2 leptons	1 lepton	no lepton
$\mu^+\mu^-$ (I)	42	35.0 ± 2.1	7.9 ± 2.9	16.9 ± 2.4	8.3 ± 1.4
$\mu^+\mu^-$ (II)	31	32.6 ± 2.0	11.0 ± 4.0	13.3 ± 2.7	1.8 ± 0.9
e^+e^-	18	23.9 ± 3.2	17.2 ± 5.6	12.8 ± 3.3	-

Table 2: Systematic errors contributing to the lifetime determination. The error sources are explained in the text.

Error source	error contribution [psec]
Decay length error scaling (A)	± 0.07
Lepton identification cuts (B)	± 0.06
Wrong track reconstruction (C)	± 0.07
J/ψ mesons from parton shower (D)	+0.05 -0.03
Background with no misidentified leptons (E)	+0.06 -0.09
Background with one misidentified lepton (F)	+0.06 -0.03
Background with two misidentified leptons (G)	± 0.02
Total (added in quadrature)	± 0.15

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Figure 1: The invariant mass distribution of $\mu^+\mu^-$ candidate pairs from selection I is shown in (a) together with the result of a fit assuming a background shape derived from the Monte Carlo and a Gaussian for the signal. In (b) the invariant mass distribution for muon pairs with equal signs is shown. The Monte Carlo estimate for the background from two muons is shown in black, the background including one misidentified muon is shown by the hatched histogram, and the background from two misidentified muons is shown by the open histogram.

Figure 2: The invariant mass distribution of e^+e^- candidate pairs is shown in (a) together with the result of a fit assuming signal and background shapes derived from the Monte Carlo. In (b) the invariant mass distribution for electron pairs with equal signs is shown. The Monte Carlo estimate for the background from two electrons is shown in black, the background including at least one misidentified electron is shown by the open histogram.

Figure 3: The x_E -dependence of the J/ψ detection efficiency for the combined lepton sample is shown in (a). The distribution of $d/dx_E Br(Z^0 \rightarrow J/\psi + X)$ for the combined lepton sample is shown in (b). Only statistical errors are included in the error bars. The dashed line shows the x_E spectrum predicted by the EURODEC Monte Carlo. The relative systematic uncertainty between the data and this prediction is 16%. The prediction for J/ψ production from gluons and secondary b quarks is shown by the shaded band, assuming a theoretical uncertainty of a factor of two.

Figure 4: Decay length distribution for the J/ψ candidates from the combined lepton sample. The curve is the result of the maximum likelihood fit to determine the lifetime.