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TOTAL CROSS SECTION FOR HADRON PRODUCTION BY e^+e^- ANNIHILATION BETWEEN 9.4 AND 9.5 GeV

by

DESY-Hamburg-Heidelberg-MPI München Collaboration

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Abstract. The total cross section for e^+e^- annihilation into hadrons for center of mass energies from 9.4 to 9.5 GeV has been measured with the nonmagnetic DESY-Heidelberg detector at DORIS. A value of $R = \sigma_{had}/\sigma_{\mu\mu} = 3.8 \pm 0.7$ for the continuum region around the $\Upsilon(9.46)$ resonance has been determined. The ratio $\Gamma_{ee}\,\Gamma_{had}/\Gamma_{tot}$ of electronic, hadronic and total width has been reevaluated to be (1.00 ± 0.23) keV for the Υ resonance and (0.37 ± 0.16) keV for the Υ'. In addition, a search for directly produced photons from Υ decays of the type $\Upsilon \to \gamma$ + gluon + gluon has been performed. The Υ decay into muon pairs has also been searched for.

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1. Introduction

In e^+e^- annihilation into hadrons the production of mesons with new flavour is expected above 10 GeV. This results in a rise of R, the ratio of the hadronic cross section to the cross section for the production of muon pairs. Between 5 and 10 GeV a 1/s behaviour of the cross section is expected and has been verified up to 7.8 GeV [1]. However, just below the Υ resonance, only one measurement of R has been published so far [2].

Here we present the analysis for the total hadronic cross section in the Υ energy range, evaluated from the data collected with the non magnetic DESY-Heidelberg detector at DORIS in summer 1978.

The same data were used previously [3] to determine the leptonic widths of Υ and Υ'. These resonances are commonly interpreted as bound quark-antiquark states. Their leptonic widths are then related to the charge of the constituent quarks and the wave function squared at the origin [4] and are therefore key parameters. They are deduced from the energy integral of the resonant hadronic cross section $\Gamma_{ee} \sim \int_{res} \sigma_{had}\, dE$. In our published analysis [3], these integrals were normalised to the hadronic cross section in the continuum region, assuming the R value published by the PLUTO group and neglecting the difference of the detection efficiencies inside and outside the resonances. We now reevaluated the leptonic decay widths of Υ and Υ', using the absolute hadronic cross section as measured in this experiment and taking into account the appropriate detection efficiencies as given by Monte-Carlo studies.

Results from the search for directly produced photons from decays of the Υ resonance, being a $J^{PC}=1^{--}$ state, should decay into three gluons, which in turn convert into hadrons. In addition the Υ resonance is expected to decay into photon gluon gluon. For this decay mode first order QCD calculations predict a branching ratio $\Gamma(\Upsilon \to \gamma + 2\text{ gluons})/\Gamma(\Upsilon \to 3\text{ gluons})$ proportional to α/α_s, the ratio of electromagnetic to strong interaction coupling constants [5].

Furthermore, the branching ratio $\Gamma(\Upsilon \to \mu^+\mu^-)/\Gamma(\Upsilon \to all)$ has been evaluated. It is also related to α_s and allows, if measured with sufficient precision, to deduce the total width of the Υ resonance.

2. Experimental set up

The non-magnetic DESY-Heidelberg detector has been described in several publications [6]. It was originally designed and especially suited for measuring total cross sections due to it's large solid angle of 86 % of 4π and flexible trigger conditions.

The inner detector consisted of three cylindrical double drift chambers which measured the direction of charged tracks, and two scintillator hodoscopes for triggering purposes. It was surrounded by an energy detector consisting of NaI and lead-glass blocks which measured the energy of electromagnetic showers with a resolution of approximately 13 % / $\sqrt{E}$ (FWHM) where E is the energy in GeV. In general, minimum ionizing particles deposited an energy of about 200 MeV in the shower counters.

Both sides and the top sections of the energy detector were covered by arrays of scintillation counters to trigger on muon pairs and reject cosmic ray background by time of flight techniques.

The whole detector in turn was surrounded by iron absorbers of 30 cm thickness on the top and bottom and 60 cm on the sides. Drift chambers surrounded the iron absorber and were used to locate the muon position over 46 % of the full solid angle.

The standard trigger for e^+e^- annihilations into hadrons required at least one charged track in the inner detector and more than 250 MeV deposited in the energy counters. For the detection of muon pairs an additional trigger was used. A coincidence between signals from two muon counters or a muon counter and one scintillator counter of the outer hodoscope on opposite sides of the detector was required together with a loose energy requirement of at least 50 MeV in the energy detector.

3. The total hadronic cross section and leptonic decay width of Υ and Υ'

The data evaluated here correspond to an integrated luminosity of 181 nb^{-1}, divided about equally into energies off and on resonance. They have been used earlier to determine the Υ resonance parameters and to evaluate the jet structure of hadronic final states and the charged multiplicity [3,7].

For the analysis of the total hadronic cross section the same event sample has been used as described in ref. [7]. The basic selection criteria were:

a) at least three charged tracks

b) at least 1800 MeV total measured energy

c) more than 5 % of the total observed energy had to appear in any half of the detector

d) at least 10 % of the observed energy had to be correlated with charged tracks

The remaining event sample was hand scanned and misinterpreted Bhabha scattering events have been removed. After this selection 1192 events remained in the energy range 9.41 to 9.52 GeV.

The background from beam-gas interactions and cosmic ray events was estimated from the vertex distribution to be 2.5 % for the events lying within the distance of ±30 mm from the interaction region. The hadronic event sample still contained a contribution from heavy lepton decays which passed the selection criteria. This contribution was estimated to be 10 % ±3 % of the continuum events and is subtracted for the determination of the hadronic cross section.

Contributions of events from two-photon annihilations were neglected. They are suppressed by the selection criteria such as the total energy cut and the requirement of at least 5 % of the total energy in each half of the apparatus.

The detection efficiency for e^+e^- annihilation into hadrons in the continuum has been calculated by a Monte-Carlo method. We used the two-quark jet model with quark fragmentation according to Field and Feynman [8]. The detection efficiency was determined to be 0.76 ±0.07. In the Monte-Carlo calculation the possibility of radiative photon emission in beam direction by the incoming e^+e^- pair was included and the photon energy was limited to half of the beam energy. It was estimated that less than 3 % of the observed events have a missing photon in the beam direction with an energy exceeding this cut. For the Υ decays a three-gluon decay model predicted an overall efficiency of 0.89 ±0.07. It should be mentioned that these Monte-Carlo simulations described well the observed sphericity and multiplicity distributions [7].

The luminosity was determined from Bhabha scattering events observed in the detector. These events were selected by requiring 2 charged particles in the drift chambers followed by electromagnetic showers in the energy detector. The total energy deposited in the energy detector had to exceed 3.5 GeV. Events with tracks near the gaps between the NaI side wall counters and the neighbouring lead glass blocks were rejected. With this cut the geometrical acceptance in the ϕ projection is 95 %. The acoplanarity angle of the two tracks and the beam direction had to be less than 15 degrees. No further acollinearity cut has been applied and events of the type $e^+e^-\gamma$ have been accepted. The cosine of the azimuthal angle θ against the beam axis had to be less than 0.7, where the $|\cos\theta|$ values have been averaged over the two tracks. 1929 events fulfilled these criteria. The calculation of the luminosity requires the knowledge of the integrated theoretical Bhabha cross section including radiative corrections. For the region $|\cos\theta|$ less than .7 and the cms energy of 9.45 GeV the lowest order cross section is 10.58 nb. Radiative corrections were calculated by the method of Berends, Gaemers and Gastmans (B.G.G.) [9] and Berends and Komen [10]. The vertex corrections and vacuum polarisation due to electrons and muons give a contribution of −0.63 nb and photon renormalization by vector mesons result in a correction of +0.28 nb. With our data selection criteria we accept more events of the type $e^+e^- \rightarrow e^+e^-\gamma$ than B.G.G. do in their paper. This excess was calculated by numerical intergration of the cross section given by Swanson [11] over the phase

space corresponding to the difference between our cuts and thos of B.G.G., it amounts to +1.1 nb. With the total Bhabha cross section of 11.3 nb a luminosity of 181 nb^{-1} is obtained.

The energy dependence of the observed hadronic cross section between 9.4 and 9.52 GeV was then fitted with a sum of a resonance curve and a continuum contribution porportional to 1/s. For the resonance curve we used a radiatively corrected gaussian resolution function [3,12]. From the continuum part the heavy-lepton contribution has been subtracted.

With the above efficiencies the fit results in a hadronic cross section of 4.06 nb for the continuum at 9.45 GeV. It should be noted again that this result includes only those radiative processes were the incoming e^+e^- particles looses less than one half of their energy by radiation.

In order to extract the ratio R, radiative corrections still have to be applied to the hadronic events. Radiative processes for the initial electrons and positrons are calculated following Bonneau and Martin [13] and lead to a contribution of −5 %. Photon propagator renormalisation and vacuum polarisation effects not included by Bonneau and Martin lead to an additional correction of −4 % [10]. Together with the total cross section for muon pair production in lowest order of QED the final value of R is 3.8 with a statistical error of 7 % and a systematical error of 11 %. The systematical error comes mainly from the uncertainty of the detection efficiencies and from the reconstruction errors of Bhabha-scattering events near the $\cos\theta$ cut of ±.7.

For the Υ'-energy range between 9.98 and 10.1 GeV, measured with lower statistics, the same analysis yields R = 3.6 with 10 % statistical and 15 % systematical error. The higher systematical error is due to some inefficient energy counters.

The integral of the hadronic cross section over the resonances $A = \int \sigma_{had}\, dE$ obtained from the fit mentioned above allows to deduce the ratio of decay widths $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot} = (E^2_{res}/6\pi^2) \cdot A$ for the Υ resonance to be (1.00 ±0.23) keV and for the Υ' resonance (0.37 ±0.16) keV. For the continuum in the Υ'-energy range, measured with low statistics, we assumed the same R value as measured for the Y-energy range. The reevaluated values differ only slightly from the previous published ones [3] of 1.04 keV for Υ and 0.32 keV for Υ'. They agree with other experiments [14,15] and favour the charge of the constituent quark to be $|e_q| = 1/3$ assuming $\Gamma_{had} \approx \Gamma_{tot}$ [16]. Using the weighted mean value for $B_{\ell\ell} = \Gamma_{\ell\ell}/\Gamma_{tot}$ from all published values [14,17] and this experiment and assuming e-μ-τ universality, the leptonic-decay width of the Υ resonance is obtained to be

$$\Gamma_{\ell\ell} = (E^2_{res}/6\pi^2) \cdot A/(1-3B_{\mu\mu}) \cdot (1-\varepsilon_\tau B_{\mu\mu}/(1-3B_{\mu\mu})) = (1.08 \pm 0.25)\ \text{keV}.$$

where $\varepsilon_\tau = 0.4$ the probability for τ decays to enter the hadronic-event sample. The measured value is in good agreement with theoretical predictions [18].

4. Search for direct production of photons from Υ decays

In order to search for the radiative decays of the Υ resonance, the hadronic event sample as defined in section 3 was used. First order QCD calculation [5] predicts for the decay process $\Upsilon \to \gamma$ + gluon + gluon a rising spectrum for the photon energy which peaks at the beam energy.

Therefore the following additional criteria were applied:

(i) The energy of the most energetic photon had to exceed 1.6 GeV.

(ii) A cone with a half opening angle of 1 rad around the direction of the most energetic photon had to be free from additional photons or charged tracks.

After a handscan we found three events outside the Υ resonance and 14 events at the Υ resonance with an integrated luminosity of 92 nb^{-1} and 89 nb^{-1}, respectively.

A major problem was that single photons could not be resolved in general from

π^0's of energy greater than 500 MeV. Another background source arises from energetic photons radiated from the incoming e^+e^- beams.

In order to isolate the radiative decays of the Υ first the background contribution of 2.9 events from the continuum under the resonance was calculated using the number of observed events outside the resonance and the ratio of integrated luminosities inside and outside of the resonance. Then the contribution of unresolved π^0's and η's from Υ decays was determined using a three-gluon decay Monte-Carlo program [7]. From this calculation a contribution of 10 background events to our event sample is expected. We then are left with a signal of one event.

Using the efficiency of 28 % for detection of the radiative decays $\Upsilon \to \gamma$ + 2 gluons $\to \gamma$ + hadrons as determined by a Monte-Carlo program we obtain for the branching ratio

$$\Gamma(\Upsilon \to \gamma + \text{hadrons})/\Gamma(\Upsilon \to \text{hadrons}) = 0.006\ ^{+0.025}_{-0.006}.$$

The rate $\Upsilon \to$ hadrons in this branching ratio may contain still about 20 % hadronic decays via one photon which have to be taken into account before comparing with the first order QCD prediction [5]

$$\Gamma(\Upsilon \to \gamma + 2\ \text{gluons})/\Gamma(\Upsilon \to 3\ \text{gluons}) = 36/5(\alpha/\alpha_s)|e_q| = 0.03$$

using $\alpha_s = 0.2$ and $|e_q| = 1/3$. Within errors the measured value agrees with first order QCD prediction and the quark charge $|e_q| = 1/3$. It should, however, been mentioned that higher order QCD corrections might be non negligable [19]. For the J/ψ resonance directly produced photons have already been observed [20,21].

5. Leptonic branching ratio $B_{\mu\mu}$ of the Υ resonance

An attempt was made to determine the muonic branching ratio $B_{\mu\mu} = \Gamma_{\mu\mu}/\Gamma_{tot}$ for the decay of the Υ resonance. Muon candidates were selected by the requirements that two tracks with an acollinearity angle of less than 21.5 degrees could be reconstructed and that the total measured energy was less than 1.2 GeV. The events had to be in time with the bunch crossing. The time of flight difference of the two particles, measured with one cosmic counter and another counter on opposite sides of the apparatus, had to agree with the calculated value within ±4 ns. It has been verified that the tracks in the inner chambers were correlated with muon-chamber hits. Remaining cosmic ray background was determined from events with tracks not passing the interaction region and indepentently from events not appearing during the bunch crossing. We finally obtained a total number of 95.7 ±10.9 muon pairs. However, we did not find any directly visible enhancement in the region of the Υ resonance.

The muon rates were fitted to a sum of a resonance cross section, 1/s QED cross section and an interference term between these two. The relative magnitude of the resonance term compared to the continuum results in a most probable value for the branching ratio $B_{\mu\mu} = \Gamma(\Upsilon \rightarrow \mu^+\mu^-)/\Gamma(\Upsilon \rightarrow all) = (1.4 {}^{+3.4}_{-1.4})$ %. This agrees with other experiments [14,17]. The quoted error arises from the limited statistics of the experiment and does not allow the deduction of the total width of the Υ resonance.

6. Conclusions

The main result presented here is the ratio R of the hadronic cross section to the cross section for e^+e^- annihilation into muon pairs. determined to be R = 3.8 ±0.7 for the continuum region near the Υ resonance. The contribution from the τ-pair production has been subtracted. It compares well with the theoretical expectation $R = 3 \sum_i q_i^2 \cdot (1 + \alpha_s/\pi) = 3.33 + 0.21 = 3.54$ summing over the charges of u, d, s, c quarks and using $\alpha_s = 0.2$. It also agrees with the value measured by the PLUTO group [2]. The reevaluated values for $\Gamma_{\ell\ell}\,\Gamma_{had}/\Gamma_{tot}$ are obtained to be (1.00 ±0.23) keV for Υ and (0.37 ±0.16) keV for Υ'. They favour a charge of the constituent quark $|e_q| = (1/3)$ e. For the investigated rare

decay channels of the Υ resonance no evidence could be found because of the limited statistics of the experiment. from the branching ratios given above we obtained for the direct production of photons from Υ decays the upper limit $\Gamma(\Upsilon \rightarrow \gamma + hadrons)/\Gamma(\Upsilon \rightarrow hadrons) < 5$ % and for the decay into muon pairs $\Gamma(\Upsilon \rightarrow \mu^+\mu^-)/\Gamma(\Upsilon \rightarrow all) < 7$ %. Both numbers correspond to the 95 % confidence level.

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