DETERMINATION OF α_s FROM A MEASUREMENT OF THE DIRECT PHOTON SPECTRUM IN $\Upsilon(1S)$ DECAYS

ARGUS Collaboration

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Using the ARGUS detector at the DORIS II e^+e^- storage ring we have measured direct photons from the decay $\Upsilon(1S)\to\gamma gg$. The ratio $R_\gamma=\Gamma(\Upsilon(1S)\to\gamma gg)/\Gamma(\Upsilon(1S)\to ggg)=(3.00\pm0.13\pm0.18)\%$ has been determined, from which we deduce values of the strong coupling constant $\alpha_s=0.225\pm0.011\pm0.019$ and the QCD scale parameter $\Lambda_{\overline{MS}}=115\pm17\pm28$ MeV defined in the modified minimal-subtraction scheme. The shape of the measured spectrum clearly rules out the predictions of the lowest order QCD calculations.

The direct photon spectrum from $\Upsilon(1S)$ decays has been measured using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The $\Upsilon(1S)$ dominantly decays into three gluons, but it can also decay into one photon and two gluons, although suppressed by order α_{em}/α_s, where α_{em} and α_s are the electromagnetic and strong coupling constants, respectively. A measurement of the inclusive photon spectrum can thus be used to determine the strong coupling constant from the ratio of the decay rates [1]

$$R_\gamma=\frac{\Gamma(\Upsilon(1S)\to\gamma gg)}{\Gamma(\Upsilon(1S)\to ggg)}$$

$$=\tfrac{4}{5}(\alpha_{em}/\alpha_s)[1+(2.2\pm0.6)\alpha_s/\pi]. \qquad (1)$$

This relation allows an accurate determination of α_s since higher order corrections almost completely cancel due to the identical structure of the leading order amplitudes of the decays $\Upsilon(1S)\to ggg$ and $\Upsilon(1S)\to\gamma gg$. The strong coupling constant is related to the QCD scale parameter $\Lambda_{\overline{MS}}$, defined in the modified minimal-subtraction scheme, by the equation [2]

$$\alpha_s=\frac{4\pi}{\beta_0\ln(Q^2/\Lambda^2_{\overline{MS}})}\left(1-\frac{\beta_1\ln\ln(Q^2/\Lambda^2_{\overline{MS}})}{\beta_0^2\ln(Q^2/\Lambda^2_{\overline{MS}})}\right), \qquad (2)$$

where $\beta_0=11-2N_f/3$ and $\beta_1=102-38N_f/3$. The number of active flavours N_f is equal to four in this case and the energy scale $Q^2=(0.157M_\Upsilon)^2$ [1].

To obtain the number of direct photons, and thus the number of $\Upsilon(1S)\to\gamma gg$ decays, the photon spectrum has to be integrated over the whole energy range. An accurate measurement of the direct photon spectrum is, however, possible only for values of $x=E_\gamma/E_{beam}$ larger than about 0.5 since at lower photon energies background photons from π^0 and η decays dominate. Thus, it is important to find a model which fits the measured part of the spectrum well, so that an extrapolation to the lower energy range may be performed confidently.

The energy spectrum of direct photons is, to the lowest order in α_s, the same as that for orthopositronium annihilation into three photons [3], which rises almost linearly with increasing energy, peaking sharply at the maximum energy. However, radiative corrections are expected to be important in the vicinity of $x=1$, leading to a slight softening of the spectrum at its upper end [4]. A parton-shower Monte Carlo approximation to QCD perturbation theory has been used to include the effect of the gluon self-coupling [5]. As the outgoing gluons radiate additional gluons they acquire invariant mass, causing the photon spectrum to vanish as the energy approaches its maximum.

The data used for this measurement of the inclusive photon spectrum from the $\Upsilon(1S)$ resonance were collected using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. The properties of the detector and its capabilities in measuring inclusive photon spectra have been described elsewhere [6,7]. The photons were detected in the shower counters which in the barrel region have an energy resolution of $\sigma/E=(0.072^2+0.065^2\,(\mathrm{GeV})/E)^{1/2}$ [8]. In this analysis the photons were restricted to the

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barrel region by an angular cut $|\cos\theta| \leqslant 0.7$, in order to take advantage of the better energy resolution and the higher trigger efficiency in this region, and to avoid the higher background from initial-state radiation in the end caps.

The event sample corresponds to an integrated luminosity of 44 pb^{-1} at the $\Upsilon(1S)$ resonance and 35 pb^{-1} in the nearby continuum from 9.4 GeV to 10.5 GeV. The data were taken during several running periods through the years 1983–1986. In order to check for possible systematic effects due to different running conditions, the data were divided into subsamples of constant experimental conditions and analysed separately. After applying corrections for detection efficiencies, which vary mainly due to different amounts of material in front of the main drift chamber, the spectra and the ratio R_γ obtained from the different periods were in excellent agreement. Therefore, only the combined data from all running periods are discussed in this paper.

In selecting multihadron events, the contributions from beam–gas and beam–wall interactions, two-photon processes and Bhabha events were suppressed by requiring that at least three charged tracks emerge from the interaction vertex, the total energy deposited in the shower counters be greater than $0.2E_{\mathrm{CMS}}$, the scalar sum of all particle momenta exceeded $0.4E_{\mathrm{CMS}}$, and at least two charged particles not be identified as electrons [#1].

In the data sample collected on the $\Upsilon(1S)$, 600 000 events remained after this selection [#2]. These include contributions from $\Upsilon(1S)\to ggg$ and $\Upsilon(1S)\to \gamma gg$ decays, nonresonant $e^+e^-\to q\bar{q}$ processes and $\Upsilon(1S)\to q\bar{q}$ decays. Most background photons from these processes come from π^0 and η decays into two photons. Fig. 1 shows the raw photon spectrum and the background contributions.

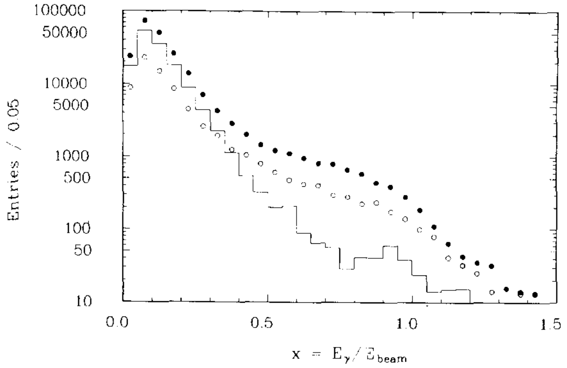

Fig. 1. The raw photon spectrum (full dots), contributions from $e^+e^-\to q\bar{q}$ and $\Upsilon(1S)\to q\bar{q}$ (open circles) and $\Upsilon(1S)\to ggg$ decays (histogram).

A photon was defined by requiring signals from at least three adjacent shower counter modules and no associated track in the main drift chamber. Photons from π^0 decays were suppressed either by cuts on the lateral shower shape [11], when both photons merged into a single cluster, or by requiring the invariant mass of any two photons to be at least two standard deviations away from the nominal π^0 mass value. In the latter case, one of the photons was also allowed to hit the endcap counters.

The inclusive photon spectrum from the continuum $e^+e^-\to q\bar{q}$ has been measured at energies off the Υ resonances. After scaling to the $\Upsilon(1S)$ energy and normalizing by the ratio of luminosities on- and off-resonance this background was subtracted.

The photon spectrum from $\Upsilon(1S)\to q\bar{q}$ is essentially the same as that from the continuum except for the absence of photons from initial-state radiation. In order to account for this, the spectrum measured in the continuum was corrected using a complete detector simulation [12] of the $e^+e^-\to q\bar{q}$ events [#3] including initial-state [14] radiation.

To determine the remaining background from $\Upsilon(1S)\to ggg$ processes, we used our measured π^0 and η spectra from direct $\Upsilon(1S)$ decays [11] as input for a Monte Carlo simulation [#3]. Cuts to suppress contributions from neutral pions to the photon spectrum were applied in the same way as described above. Losses for detector acceptance were taken into account as well as merging of two-photon clusters, overlaps of a photon and a charged particle, and conversion of photons into e^+e^- pairs in the material prior to the main drift chamber.

A small background of less than 0.5% from neutral hadronic showers in the region $x<0.5$ was largely re-

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[#1] Electrons are identified by means of their energy loss in the drift chamber, their time of flight, their energy deposition in the shower counters and the lateral shape of the shower, using a likelihood method. The procedure is described in ref. [9].

[#2] For a detailed description of the analysis see ref. [10].

[#3] The event generator used was Lund 6.2. For details see ref. [13].

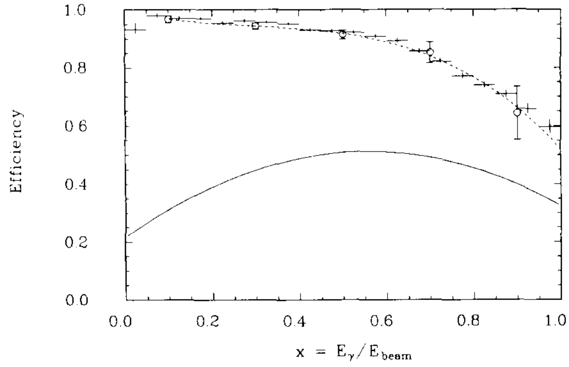

Fig. 2. The total acceptance (solid curve) for detection of photons in the decay $\Upsilon(1S)\rightarrow\gamma gg$ and the efficiency due to the cut in event multiplicity determined from the data (circles) and from Monte Carlo calculations (crosses). The dotted curve is a fit to the data. Indicated are statistical errors only.

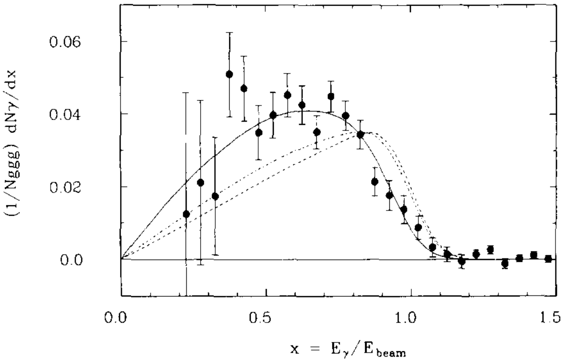

Fig. 3. Acceptance-corrected direct photon spectrum compared to the theoretical spectra of ref. [3] (dashed curve), ref. [4] (dot-dashed curve) and ref. [5] (solid curve). The error bars represent statistical errors only.

moved by the cut in the lateral shower shape. The remaining background from hadronic showers was estimated using a Monte Carlo detector simulation [12] in combination with a simulation of hadronic showers [15].

After background subtraction the spectrum was corrected for acceptance losses, reconstruction inefficiencies, conversion losses, losses due to overlaps with charged tracks and for inefficiencies of the selection criteria, using simulated $\Upsilon(1S)\rightarrow\gamma gg$ events. An angular distribution of the form $dN/d(\cos\theta) = 1+a(x)\cos^2\theta$ was assumed for the direct photons, with the value of $a(x)$ taken from calculations of the orthopositronium decay [16]. The acceptance curve was found to be essentially independent of the shape of the photon spectrum assumed. The resulting acceptance has a maximum of 52% at $x=0.55$ and falls smoothly to 33% at $x=1$, as shown in fig. 2. This fall-off is due to the requirement of at least three charged tracks in the event, since the invariant mass of the gluons becomes smaller; thus the average multiplicity decreases as the energy of the photon increases.

The acceptance-corrected direct photon spectrum in the range $x=0.2$–1.5 is shown in fig. 3. In order to integrate this spectrum we compare our data with the theoretical models mentioned previously, after folding them with the energy resolution of our shower counters. Data points for $x<0.5$ were not included in the fit because of their larger statistical and systematic errors. They are nevertheless included in the figure to show that they are consistent with the expected shape of the photon spectrum. Furthermore the data points in the region $x>1$ are leveling off at zero as expected. These two facts give confidence that the background subtraction is done correctly. In a linear least-squares fit, only the overall normalization enters as a free parameter. The prediction of ref. [5] describes the data very well, with a χ^2 of 9.2 at 13 degrees of freedom. The spectra of refs. [3,4] are clearly ruled out, having χ^2 values of 78 and 53, respectively.

To check that the softening of the spectrum is not artificially produced by the requirement of at least three charged particles in the event, a sample of about 12000 $\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ decays was studied. This sample was selected in the same way as described in ref. [17]. Allowing the two pions alone to provide the trigger, and without imposing a multiplicity cut, a completely unbiased $\Upsilon(1S)$ sample is obtained. After background subtraction the remaining 6300 events were used to experimentally determine the efficiency of the cut in the event multiplicity. Comparison with the Monte Carlo calculation (fig. 2) shows excellent agreement. From the efficiency spectrum the contribution of the multiplicity cut to the systematic error was obtained.

As a detailed investigation has shown [10], the other major contributions to the systematic error come from uncertainties in the photon selection procedure and in the background subtraction from $\Upsilon(1S)\to ggg$ events. In addition, we considered errors due to uncertainties in the trigger efficiency, in the event selection not including the multiplicity cut, in the relative luminosity measurement, in the $\Upsilon(1S)$ yield due to the energy calibration of the storage ring, and in the branching ratio of $\Upsilon(1S)\to q\bar{q}$. Each of these contributed less than a percent. All systematic errors that depend on the photon energy were properly weighted with the measured direct photon spectrum to give the total relative systematic error on the overall scale of σ/R_γ of 6.0%.

Fitting the spectrum of ref. [5] to our data gives the total number $N(\gamma gg)=11\,110\pm 460$ of $\Upsilon(1S)\to\gamma gg$ decays. From the observed number of hadronic decays of $\Upsilon(1S)$, the number of three-gluon decays $N(ggg)=369\,000\pm 7400$ is calculated using $B_{\mu\mu}=\mathrm{Br}(\Upsilon(1S)\to\mu^+\mu^-)=0.028\pm 0.002$ [18]. This gives the ratio

$$R_\gamma=\frac{\Gamma(\Upsilon(1S)\to\gamma gg)}{\Gamma(\Upsilon(1S)\to ggg)}=(3.00\pm 0.13\pm 0.18)\%\,,$$

from which we find

$$\alpha_s=0.225\pm 0.011\pm 0.019$$

and

$$\Lambda_{\overline{MS}}=115\pm 17\pm 28\ \mathrm{MeV},$$

where the theoretical uncertainty of eq. (1) has been added in quadrature to the systematic error.

Our values of α_s and $\Lambda_{\overline{MS}}$ are in good agreement with previous results from measurements of R_γ [19,20], and consistent with results from recent measurements in e^+e^- annihilation at $\sqrt{s}$ of 30 GeV–45 GeV [#4], deep inelastic scattering [23], and with calculations of $\Gamma_{ggg}/\Gamma_{\mu\mu}$ at the J/ψ and Υ resonances [24] [#5]. However, the shape of our photon spectrum is in clear disagreement with that of ref. [19].

In conclusion, we have measured the direct photon spectrum from $\Upsilon(1S)$ decays, confirming the spectral shape of ref. [5]. Using this shape to extrapolate our measured photon spectrum to $x=0$, the ratio R_γ provides a precise determination of the strong coupling constant α_s and the QCD scale parameter $\Lambda_{\overline{MS}}$.

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